Liquid Distribution And Falling Film Wetting In Dairy Evaporators

A thesis
submitted in fulfilment
of the requirement for the
Degree of Master of Engineering

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Christchurch, New Zealand
2005

Abstract

Niro designed and built five near-identical milk evaporators for Fonterra's production site at Clandeboye and five at the Edendale site. Tubes in the Clandeboye evaporators often fouled excessively and occasionally blocked, requiring water blasting to clear them. Large amounts of undesirable foam from milk were observed in the second effect of some evaporators. This was known to be related to fouling and early shutdowns. The fouling increased the cleaning chemical and utility usage, and the evaporator downtime. The problems were believed to be related to the liquid distribution system at the top of the tubes.

Evaporator liquid distribution has received relatively little research but it has been shown that the efficiency of evaporation reduces when there is poor wetting. Some estimates were available from previous work for the minimum flowrates required to obtain a complete falling film inside a tube.

Many tasks were performed to assess the performance of the liquid distribution systems. The minimum wetting rates of three different milks were found in a model evaporator tube under isothermal, heat transfer and evaporation conditions at 60ºC. Numerous measurements of evaporators at Clandeboye were made to thoroughly analyse the evaporator performance. The overall heat transfer coefficients and wetting rates were calculated throughout the evaporators.

Physical measurements were taken of the dimensions of the distribution systems in every evaporator. Many potential problems were found including warping, inconsistent hole sizes and fabrication faults. An analysis of the tube and distribution hole arrangements showed that every pass had some liquid misdistribution which was confirmed by a water trial.

The evaporators were inspected before cleaning after 22 hours of whole milk production and after 5 hours of milk protein concentrate (MPC) production. There was considerable fouling at the bottom of some tubes that received low whole milk flows and large particles of MPC were blocking distribution plate holes.

Observation and analysis showed that the foaming was likely to be caused by an upward flow of vapour from some passes which disrupted the downward flow of milk.

As a result of this project there is sufficient confidence to justify modification of effects 2 and 4 of the evaporators. Sixteen tubes in effect 4 will be welded shut and the distribution systems in effects 2 and 4 will be redesigned to give a better liquid distribution.

For effect 2, vertical tubes called ‘vapour risers’ should be installed to allow the vapour to flow upwards through the distribution plate without creating foam. The heights of the partitions dividing the effect 2 passes will be modified to encourage any foam in pass 1 to flow preferentially to pass 2. Installing a filter after the MPC direct steam injector will reduce the number of blocked distribution plate holes.

Both modifications are expected to enable the evaporators to run continuously for 20 hours instead of 15 hours, giving up to 33% fewer cleans. The cleaning costs are approximately $700 and milk losses are approximately $200 per clean. The modifications should save up to $438,000, based on cleaning and water blasting in the 2003-2004 milk powder season.

The design of future evaporator distribution systems must be improved to avoid retrofitting.

Acknowledgements

Many people have helped me in this project and I am grateful for their efforts.

Fonterra Co-operative Limited generously funded my university fees and the facilities for this project to take place.

I am extremely grateful to Technology New Zealand for their financial support of this project, especially when the cost of petrol kept on increasing throughout the year. Dr. Ken Morison, Dr. James Winchester and Technology New Zealand made this project possible. James was a great mentor. Ken has been an outstanding supervisor.

There are many support staff at Clandeboye to thank. John Gabites was a great workmate when he finally arrived for his long-haul PhD at Clandeboye. I gave Bronwyn Nunn's lab team over a thousand total solids samples to do during my time and their hard work was the backbone to the data for this project. The A, B, C and D powder shifts were on the whole very patient with me roaming around the plant even though they didn't really know why I was there. Fiona Russell organised the trip to Edendale in July in the blink of an eye, and almost always had digital cameras handy.

Andrea Wilson and Frammy (Keith Frampton) were the most hospitable hosts I could have hoped for when I moved to Timaru. Port FM was an interesting radio station.

I would also like to thank many members of the Christchurch Church of Christ for their support and guidance – before, during and after my time in Timaru. I really appreciated the help from Stewart Sluis and Jimmy Schuster for their lounge floor during my trips to Christchurch, and also for Tim and Deborah Radeka's hospitality during the off-season. Amongst others, I appreciate the help from Paul and Erin Norrie, Jules Josland, Anthony York, Susi Sireger and Sarah Garmson, Jason Clamp, Marcel and Sarah Vickers, James and Cathy Newbigging, Marc and Karen Wilson, Michelle Kite and Stewart Sluis, Sarah Burgess and Kim Georgine, Frances Wilson and Glenn Brittain.

My deepest sympathy goes the families of James Mansfield who died on 25 August 2004 and Kiel Nolly was killed during a motorcycle crash on 3 April 2005.

Table of Contents

Nomenclature

Roman Symbols

Symbol	Explanation	Value & Units
A	Inner surface area of tubes	m^2
a_w	Water activity	–
Cp_{milk}	Specific heat capacity of milk	$J\ kg^{-1}K^{-1}$
d_i	Inside diameter of tube	m
d_o	Outside diameter of tubes	50.8 mm, 2”
h_i	Internal heat transfer coefficient, IHTC	$W\ m^{-2}K^{-1}$
h_o	External heat transfer coefficient, EHTC	$W\ m^{-2}K^{-1}$
k_l	Thermal conductivity of liquid	$W\ m^{-1}K^{-1}$
k_s	Thermal conductivity of stainless steel	$W\ m^{-1}K^{-1}$
L	Length of tubes	14 m
$\dot{m}_{evap}$	Mass evaporation rate in a pass	$kg\ s^{-1}$
$\dot{m}_{flash}$	Mass flowrate of flashing in a pass	$kg\ s^{-1}$
$\dot{m}_{in}$	Mass flowrate of liquid into the pass	$kg\ s^{-1}$
$\dot{m}_{out}$	Mass flowrate of liquid out of pass	$kg\ s^{-1}$
n_{holes}	Number of distribution plate holes in the pass	–
n_{tubes}	Number of tubes in a pass	–
q	Volumetric flowrate of liquid	$m^3\ s^{-1}$
Q	Energy used in evaporating milk in a pass	J
R	Universal Gas Constant	$8.314\ J\ mol^{-1}K^{-1}$
Re_L	Reynolds number at base of tube	–
t	Thickness of tubes	1.245 mm
T_{effect}	Temperature of effect	ºC
T_{enter}	Temperature of milk entering effect	ºC
T_{shell}	Temperature of shell	ºC
T_{wb}	Boiling Temperature of water	273.15 K
TS	Total Solids	% w/w
TS_{av}	Average total solids concentration in a pass	% w/w
TS_{feed}	Total solids of feed milk at balance tank	% w/w
TS_{in}	Total solids concentration into a particular pass	% w/w
TS_{out}	Total solids concentration out of a particular pass.	% w/w
U	Overall Heat Transfer Coefficient	$W\ m^{-2}K^{-1}$

Greek Symbols

Symbol	Explanation	Units
δ_m	Mean film thickness	m
δ_{min}	Minimum thickness of film	m
Δh_v	Latent heat of vaporisation	J kg^{-1}
ΔT	Shell-to-effect temperature difference	ºC
ΔT_b	Boiling Point Elevation	ºC
γ	Interfacial tension	N m^{-1}
Γ_L	Wetting rate of condensate at base of tube	kg $m^{-1}s^{-1}$
Γ_{min}	Minimum wetting rate	kg $m^{-1}s^{-1}$
Γ_{out}	Average outlet wetting rate from a pass	kg $m^{-1}s^{-1}$
$\Gamma_{low,out}$	Lowest outlet wetting rate from a pass	kg $m^{-1}s^{-1}$
μ_l	Dynamic viscosity of liquid	kg $m^{-1}s^{-1}$
μ_L	Dynamic viscosity of liquid at base of tube	kg $m^{-1}s^{-1}$
θ	Contact angle of liquid	^{o}
ρ_l	Density of liquid	kg m^{-3}
ρ_v	Density of vapour	kg m^{-3}
σ_l	Surface tension of liquid	N m^{-1}

Abbreviations

Abbreviation	Explanation
ASTM	American Society for Testing and Materials
CD1	Fonterra Clandeboye’s Dryer 1
CD2	Fonterra Clandeboye’s Dryer 2
CD3	Fonterra Clandeboye’s Dryer 3
CPS	Carlisle Process Systems
DSI	Direct Steam Injection (and Injector)
ED2	Fonterra Edendale’s Dryer 2
ED3	Fonterra Edendale’s Dryer 3
MPC	Milk Protein Concentrate
MPC-70	Milk Protein Concentrate with 70% dry basis protein content
MPC-85	Milk Protein Concentrate with 85% dry basis protein content
MVR	Mechanical Vapour Recompression
NZ	New Zealand
TVR	Thermal Vapour Recompression

1. Introduction

1.1 Background

1.1.1 Evaporation in New Zealand

The New Zealand dairy industry converts significant amounts of fresh milk into spray dried milk powder. The milk is dried in two steps: evaporation and drying. In the dairy industry, evaporation refers to the removal of the water from the solution, where the product is a concentrated liquid. Technically, spray drying is also an evaporation process, but as the product from a dryer is powder, this is termed as drying.

Evaporators are much more efficient than a spray dryer so they are used to concentrate milk as much as possible before drying. The efficient performance of evaporators is vital for the dairy industry and the New Zealand economy. There are approximately 50 dairy evaporators in New Zealand, mostly owned by Fonterra. Over 800,000 tonnes of milk powder are produced annually in New Zealand.

Falling film evaporators are suitable for milk because they can operate between 48ºC and 75ºC, have high heat transfer coefficients and their low temperature differences minimise heat damage to the proteins. The absence of a static head gives low boiling point elevations and pressure drops, and short residence times.

These evaporators remove most of the water in milk, concentrating it from typically between 10% and 13% total solids (TS) to approximately 50% TS. The energy source is indirect heating by steam, which gives temperature differences between 2ºC and 10ºC.

Two companies supply evaporators to Fonterra. One is Niro A/S, which is a core company in the Process Engineering Division (P-Division) of GEA. The other is Carlisle Process Systems, or CPS, which makes Stork evaporators. Both companies build milk powder spray dryers and supply evaporators with them.

This project studied in detail five Niro evaporators at Fonterra Clandeboye's milk powder plants. Five identical evaporators at Fonterra Edendale were briefly studied.

Fonterra Clandeboye and Edendale each have three milk powder plants. The names and abbreviations are shown in Table 1-1. Edendale’s Dryer 1 and Clandeboye’s Dryer 3 were not studied.

Table 1-1: Abbreviations for the milk powder plants at Fonterra Clandeboye and Edendale.

Site and Dryer	Abbreviation	Design Company
Clandeboye Dryer 1	CD1	Niro GEA
Clandeboye Dryer 2	CD2	Niro GEA
Clandeboye Dryer 3	CD3	CPS (‘Stork’)
Edendale Dryer 2	ED2	Niro GEA
Edendale Dryer 3	ED3	Niro GEA

1.1.2 Milk Products

Fonterra Clandeboye spray dries three main types of milk in its powder plants. These are whole milk, skim milk and milk protein concentrate (MPC). Whole milk is unseparated cows milk which contains fat, protein, sugars and minerals. Skim milk has most fat removed by centrifugation. Milk protein concentrate (MPC) is milk which has been ultra-filtered to remove some of the sugars and minerals, increasing the concentration of the proteins. Clandeboye processes MPC-70 and MPC-85. These milks have 70% and 85% protein contents respectively on a dry basis.

CD1 processes skim and whole milks. CD2 processes skim and whole milks, and MPCs. The newly commissioned Dryer 3 (CD3) processes whole milk.

A variety of pasteurisation heat treatments and holding times are available according to customer requirements. Milk can be put under low heat, medium heat or high heat treatment. Typical treatment temperatures are 75 to 85ºC for low heat, 85 to 105ºC for medium heat and 105ºC to 125ºC for high heat. Milk can be held for between 10 and 180 seconds, depending on the product specifications and the Whey Protein Nitrogen Index, which is a measure of unreacted proteins.

1.1.3 Physical Construction and Operation of Falling Film Evaporators

There are many types of evaporators available for concentrating liquids, depending on the physical properties of the solution, the end use of the product and the scale of operation. Falling film evaporators are currently the most suitable means for concentrating large amounts of milk for powder production.

A falling film evaporator consists of a body which contains many vertical tubes whose ends are welded into plates. This body is commonly referred to as the *calandria*, and the metal plates at the top and bottom containing the tubes are called the *tubesheets*. The tubesheets physically separate the inside of the tubes from the outside of the tubes.

A calandria can hold anywhere from 30 to 1700 tubes. They can be up to 18 m long. The tubes in Clandeboye's Niro evaporators are 14 m tall. The tubes had an outer diameter of 50.8 mm (2 inches). They had a metal thickness of 1 mm.

Figure 1-1 shows the typical components of a falling film evaporator. It consists of a liquid distribution section at the top, a calandria in the middle and a vapour-liquid separation zone at the bottom.

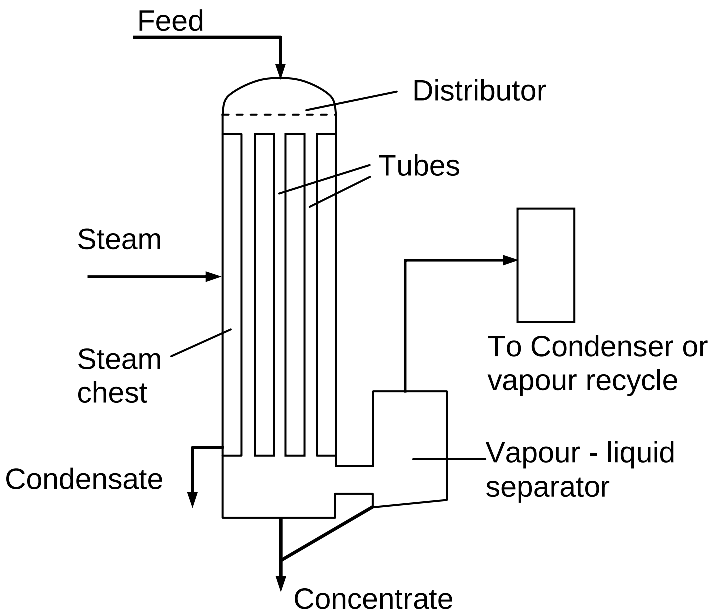


Figure 1-1: The typical components of a falling film evaporator.

Milk enters the evaporator at the top and flows onto a distributor. This transfers the milk to the top of the tubesheet, so that it fully coats the insides of the tubes and flows downwards as a falling film.

Saturated steam heats the outside of the tubes by condensing. The heat travels through the tube wall and causes the milk on the inside of the tubes to evaporate. The steam side is referred to as the *shell* and the milk side is called the *effect*. Figure 1-2 shows the transfer of heat in an evaporator tube (TetraPak, 2000).

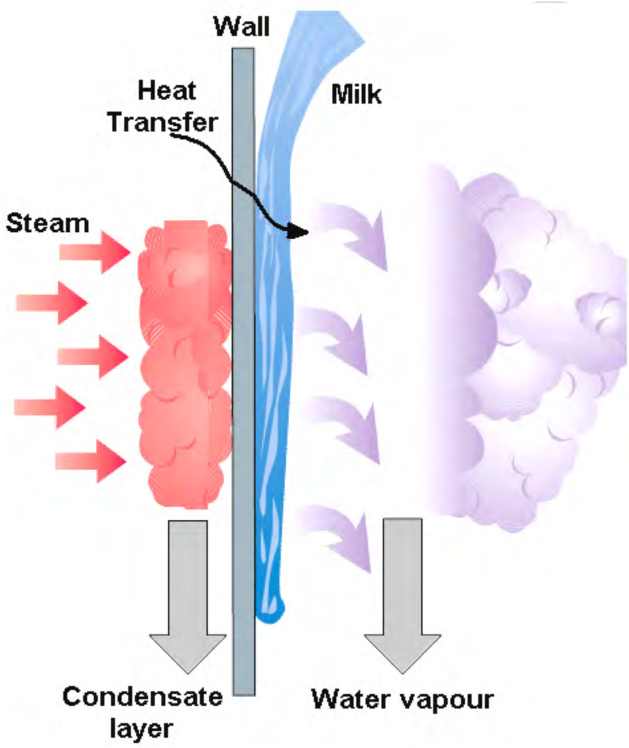


Figure 1-2: The heat and mass flows occurring in a falling film evaporator tube (TetraPak, 2000).

Water vapour from the milk flows down through the tubes, co-currently with the milk. This is reported to improve evaporation (Jebson and Iyer, 1991). The liquid film becomes thinner as the liquid flowrate decreases.

A vapour-liquid separation zone typically exists at the bottom of the calandria. Milk falls downwards through an open cavity, while water vapour flows sideways into a separator. The separator removes entrained milk droplets from the vapour. The milk streams recombine and the vapour goes to be recycled or condensed.

1.1.4 Vapour Recycling

A considerable amount of energy is required to evaporate water from milk, especially on the scale at Fonterra Clandeboye. The CD1 dryer produces approximately 13 t h^{-1} of milk powder, consuming up to 130,000 L h^{-1} of skim milk per hour. This gives an evaporation rate of up to 104,000 kg h^{-1}. The energy required to evaporate the milk from 10% to 50% total solids is approximately 68 MW. As Fonterra Clandeboye has three milk powder plants with capacities of 13 t h^{-1}, 14 t h^{-1} and 24 t h^{-1}, the energy requirement is very large and efficient use of energy is required.

Direct Steam Expansion

The evaporated water vapour contains a considerable amount of energy, which is wasted if the vapour is discarded. Energy savings are available by recycling this water vapour in what is termed *multi-effect* or *direct steam expansion* evaporation. Figure 1-3 shows a multi-effect evaporator.

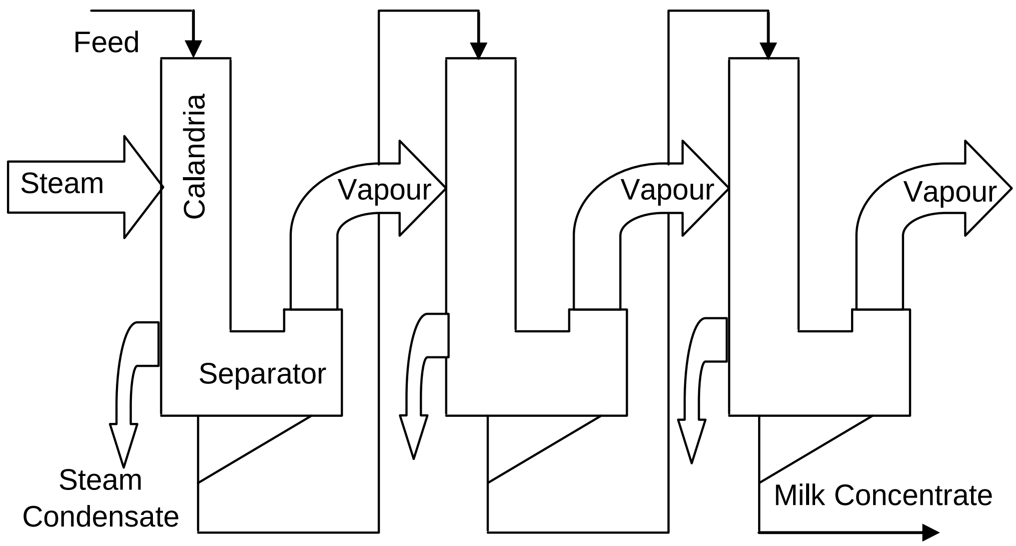


Figure 1-3: Multi-effect evaporation involves taking the evaporated water vapour from an effect, and using it as heating steam for the following effect.

The energy usage in a multi-effect evaporator decreases by approximately $1/n_{effects}$. For example, a two-effect evaporator uses half the energy of a single effect evaporator. The energy savings are offset by the increased capital cost of building extra effects. Fonterra's Te Rapa site has a seven-effect evaporator. Clandeboye's Niro evaporators each have four effects.

Further efficiency is available by extracting some water vapour from an effect, increasing its temperature and feeding it to an earlier effect. Two methods are explained in the following subsections.

Thermal Vapour Recompression (TVR)

TVR uses high pressure steam to compress water vapour from a downstream effect. The steam is passed through a thermo-compressor which acts like a venturi, sucking a proportion of the water vapour from the downstream effect, and compressing it into steam suitable for heating the tubes. This can give an increase in pressure equivalent to a temperature rise of 12 to 20ºC (Morison, unpublished). A stable steam supply from 4 to 8 bar gauge pressure is suitable for TVR.

Figure 1-4 shows a typical TVR around one effect. This gives more heating to the first effect. The water vapour can come from any one of the downstream effects. Typically, vapour from two effects downstream is recycled. Installing a TVR unit gives approximately the same increase in efficiency as adding an extra effect.

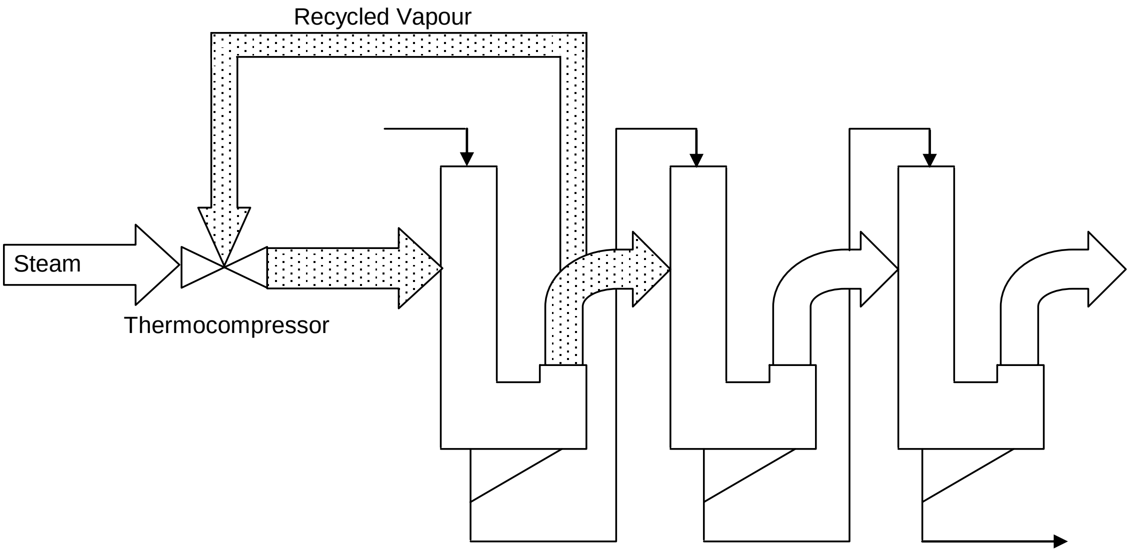


Figure 1-4: A thermo-compressor takes water vapour from a downstream effect and compresses it with typically 8 bar gauge steam to heat an effect.

Mechanical Vapour Recompression (MVR)

Fans or turbines can be used as an alternative method to increase the pressure of the water vapour. Radial fans are typically used in modern plants because they are simple to operate and cost considerably less than compressors. Unfortunately, they offer only a small increase in temperature, typically 4 to 6ºC. Two fans must be joined together in series to achieve larger temperature differences. The choice between using MVR and TVR is largely determined by the cost of steam and electricity, and the scale of operation. The small temperature difference offered by radial MVR fans requires that the evaporator has a large surface area.

1.1.5 Clandeboye's Niro Evaporators

The Niro evaporators at Fonterra Clandeboye are *4-effect co-current and forward flow falling film MVR-TVR bi-therm units.* This means there are two MVR effects and two TVR effects, that the liquid flows from effect 1 to 4 in sequence, and there is a TVR unit installed over the last two effects.

Evaporation and the heat treatment of milk are intimately related. Table 1-2 shows the steps involved with heat treatment and evaporation. Concentrate storage and spray drying followed evaporation.

Table 1-2: Explanation of the steps in evaporating milk in the Niro evaporators.

Step	Purpose
Feed Buffer Tank	Cold raw milk is pumped in.
Preheating in PHE	Evaporator condensate heats the milk to approximately 50ºC.
Integrated preheating effects 2 and 1	Preheaters use steam from effects 2 and 1 to heat the milk to approximately 60ºC. This doubles as a means to remove non-condensable gases, which can hinder heat transfer if present.
Direct Contact Heaters	None, one or two are used. Condensing steam heats the milk.
Direct Steam Injection (DSI)	This injects steam to pasteurise the milk.
Holding Tubes	The milk is held at temperature for a specified time. This can be from 10 to 180 seconds.
Flash Vessels	The milk is passed into a low pressure vessel, where the milk flash evaporates to cool. This provides steam for the direct contact heaters. None, one or two flash vessels can be used.
Evaporation	Milk passes through four effects, concentrating from approximately 10% to 50% total solids.

Fonterra’s CD1 plant was built in 1997. It contained Evaporators 1 and 2. The CD2 plant was built in 2000 and contained Evaporators 3, 4 and 5. Edendale’s ED2 and ED3 plants contained five evaporators which were most similar to the CD2 evaporators.

Figure 1-5 shows the configuration of the CD1 evaporators. Figure 1-6 shows the CD2 evaporator configurations.

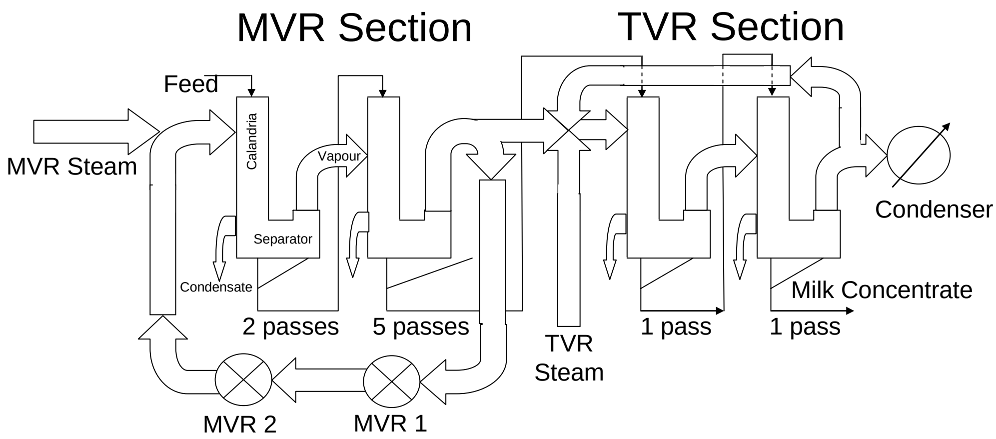


Figure 1-5: Process flow diagram of Clandeboye’s Evaporators 1 and 2 (CD1).

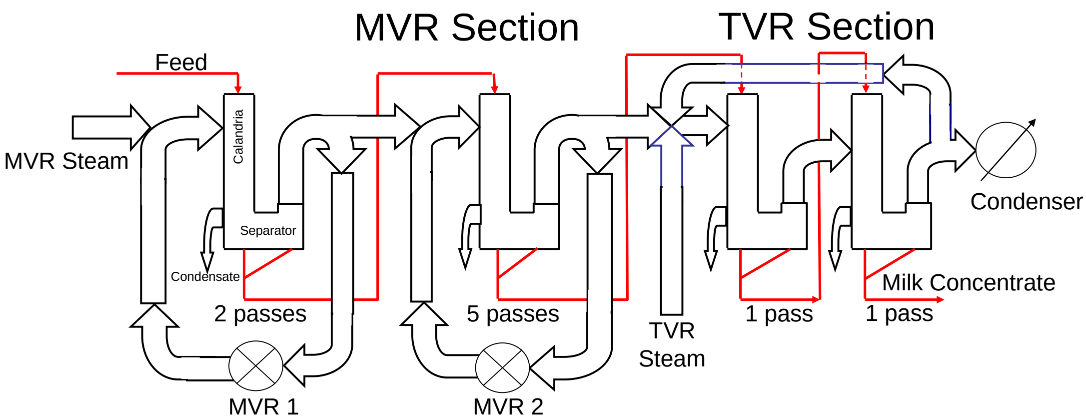


Figure 1-6: Process flow diagram of Clandeboye’s Evaporators 3, 4 and 5 (CD2).

Vapour Recycling Systems

The MVR fan configurations were different in CD1 and CD2. In CD1 the vapour from effect 1 was used to heat effect 2. The vapour from effect 2 was compressed using two MVR fans in series to heat effect 1. The MVR fan speeds were adjusted according to the density out of effect 2. There was no measurement or control of the density out of effect 1.

In CD2, the vapour from effect 1 was compressed in an MVR fan to heat effect 1. The vapour from effect 2 was recompressed in the other MVR fan to heat effect 2. There was a flow of water vapour from effect 1 to the shell of effect 2. This allowed the evaporator to act as a direct steam expansion evaporator, with temperatures that reduced along each effect.

The MVR fan configuration in the CD2 evaporators gave better temperature control than the configuration in CD1. The ED2 and ED3 evaporators were built after CD2 and have the CD2 design.

Stork evaporators, such as those in Clandeboye's Dryer 3, had the two MVR calandrias working at the same pressures. This made them act as a single effect. This configuration is reported to make the evaporators easier to control (James Winchester, personal communication, 2004).

Effects 3 and 4 were TVR sections. They were both single-pass units which were supposed to control the total solids of the milk concentrate exiting the evaporators. The vapour from effect 3 was used to heat effect 4. Steam at a pressure of approximately 8 bar gauge pressure was used to compress some water vapour extracted from effect 4 and some water vapour from effect 2. This was sent to heat effect 3. The remaining water vapour from effect 4 was condensed to maintain a vacuum through the evaporator. There were two TVR nozzles, allowing a variety of steam flowrates.

There are pressure and temperature sensors for every shell and effect of the CD1 and CD2 evaporators, and there are density-flow meters at the outlets of effects 2 and 4.

Vapour-Liquid Separators

The CD1 evaporators had separate vapour-liquid separators for effects 1 and 2. The CD2 evaporators instead had a *wrap-around* vapour separation zone around the bottom of effects 1 and 2. These are shown in Figure 1-7.

Integrated vapour separators reduced floor space and the need for an extra vessel. The effect 3 and 4 separators in the CD1 and CD2 evaporators were separate vessels and were all identical.

Flow Configurations and Operating Conditions

Table 1-3 shows the configuration of passes in the Niro evaporators. They have a *123456789* forward-flow configuration. This means the liquid passes through both passes of effect 1, then all five passes of effect 2 and then through effects 3 and 4.

There was some flash evaporation in the first pass of each effect. This was because the pressure was lower than the previous effect, and the liquid was superheated when it entered the effect.

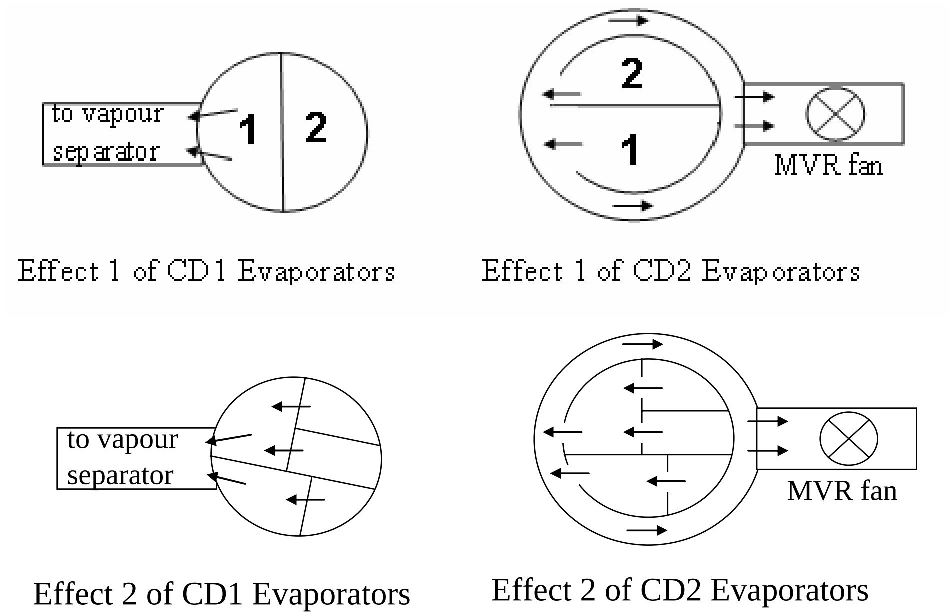


Figure 1-7: The CD1 evaporators have a separate vapour separator, while the CD2 evaporators have an integrated 'wrap-around' vapour separator.

Table 1-3: The number of passes, the typical operating temperatures and the temperature differences (ΔT) in CD1 Evaporator 2 on skim milk.

Effect – Pass	Number Of Passes	Typical shell temperature, ºC	Typical effect temperature, ºC	Typical ΔT, ºC
1	2 Passes	73	70	3
2	5 Passes	69	66	3
3	1 Pass	64	60	4
4	1 Pass	58	48 to 50	4 to 10

Operating Flowrates and Outlet Total Solids

The evaporator fan speeds were higher for skim milk than whole milk. This was because skim milk had higher feed flowrates and lower inlet total solids concentrations, requiring more evaporation. Table 1-4 shows the typical total solids concentrations and flowrates entering and exiting the evaporators.

Table 1-4: The typical total solids concentrations and flowrates entering and exiting Clandeboye Evaporators 1 to 5 while processing skim and whole milks.

Milk	Total Solids Concentration: Inlet %	Outlet, %	Flowrates: Inlet, t h^{-1}	Outlet, t h^{-1}
Skim	9.9	49.9	63.7	12.7
Whole	13.1	51.0	44.0	11.3
Uncertainty ±	1	4	4	1

There is an upper limit to the viscosity of milk concentrate entering the dryers. Typically, skim and whole milks are concentrated up to 50% total solids before drying. Wood (1982) shows that the viscosity of whole milk is considerably lower than skim milk. Unless there are solubility issues, the total solids of whole milk entering the dryers should be higher than skim milk.

MPC Production

Evaporators 3 and 4 can run with three effects for MPC production. This uses only effects 2, 3 and 4, and requires one MVR fan instead of two. The outlet concentration of MPC from the evaporators is between 25% and 30% total solids. The fan speed is lower than for skim or whole milks. The steam used for preheating the feed comes from effects 2 and 3, rather than effects 1 and 2. This changes the nature of operation slightly.

1.1.6 Liquid Distribution Systems & Falling Film Wetting

Goals of Distribution Systems

An evaporator cannot function efficiently with poor liquid distribution. The objectives of liquid distribution systems are as follows:

- To give equal flows into each tube around the entire circumference,
- to take care of flash vapours without interfering with liquid distribution,
- and to give the milk an acceptably low residence time.

Cleaning fluids should be able to overflow to clean all surfaces, especially the underside of the distribution plates (Ken Morison, unpublished, p. 41).

Distribution Plates

Efficient evaporation requires milk to be distributed around the inner periphery of the evaporator tubes and down the entire length. There must be no dry patches at all. Figure 1-8 shows how a distribution plate transfers liquid onto the tubesheet and then to the inside of the evaporator tubes.

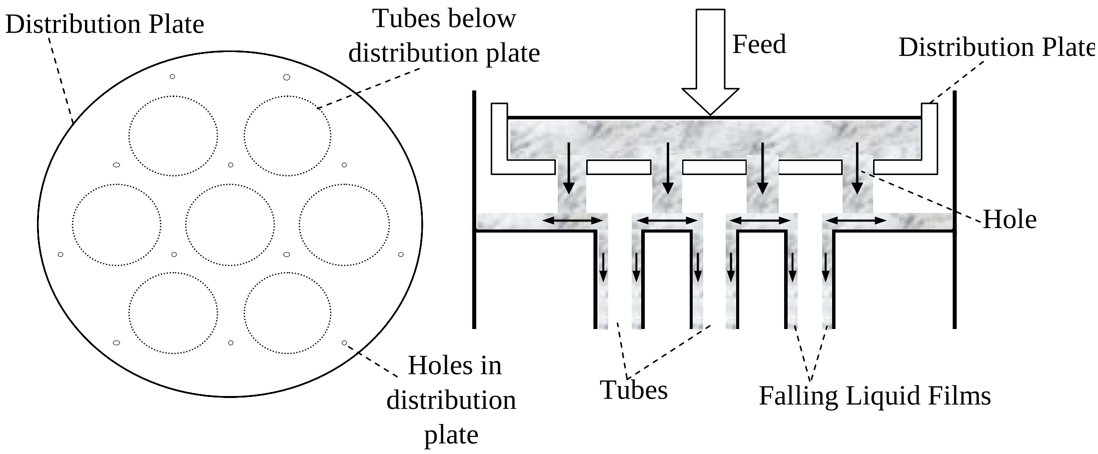


Figure 1-8: A distribution plate transfers milk to the tubesheet through holes, where it spreads on the tubesheet and forms a falling film on the inside of the evaporator tubes.

Hole Configurations

Distribution plates can have three or six holes surrounding each tube. Niro evaporators surrounded each tube with three holes, while Stork evaporators surrounded each tube with six holes. This is illustrated in Figure 1-9 and Figure 1-10. The use of six holes is expected to spread the liquid better on the tubesheet. Unfortunately, using six holes means that for a given liquid head height, the hole sizes are smaller. This makes it easier for holes to block.

Figure 1-9: Niro's three-hole design **Figure 1-10: Stork's six-hole design.**

Flash Vapours

There was a small amount of flash evaporation above the distribution plate as superheated milk entered each effect and cooled to the appropriate temperature. The low pressures ensured that a large volume of vapour formed for a small amount of flashing. Space must be given for these flash vapours to flow down the tubes without disrupting liquid distribution.

The Stork distribution plates were essentially flat metal disks with holes drilled in them. The distribution plate was sandwiched between the tubesheet and the calandria lid. Stork evaporators used *vapour risers* to transport the flash vapours directly into the evaporator tubes. These were small upraised tubes welded into the distribution plate, as shown in Figure 1-11. The distribution plates were supported by partitions or pins on the tubesheet.

Niro preferred to direct flash vapours around the side of the distribution plate. There were no vapour risers. This is illustrated in Figure 1-12. A Niro distribution plate looked like a large cake tin with holes drilled in the bottom. A gap was provided between the edge of the distribution plate and the calandria wall to enable the vapour to flow down the tubes without disrupting liquid distribution. The distribution plates rested on partitions on the tubesheet or on pin supports and the plates did not touch the calandria lid.

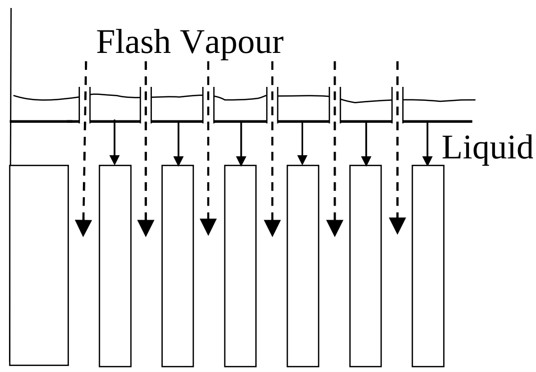


Figure 1-11: Stork evaporators use vapour risers to divert flash vapours down tubes.

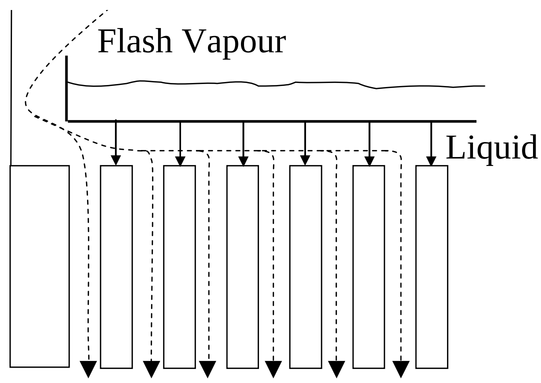


Figure 1-12: Niro evaporators send flash vapours around the side of the distribution plate and then down tubes.

Product Transfer Systems

There are different systems available for transferring liquid from the inlet pipe to the distribution plate. Niro used a *spray plate* to deflect the inlet liquid sideways to the inside of a *deflector basket*, commonly called the *basket*. The liquid then fell downwards onto the distribution plate and through the distribution plate holes to the tubesheet. Figure 1-13 shows the Niro product distribution system. Stork evaporators sprayed the liquid directly onto the distribution plate from the inlet pipe, as shown in Figure 1-14.

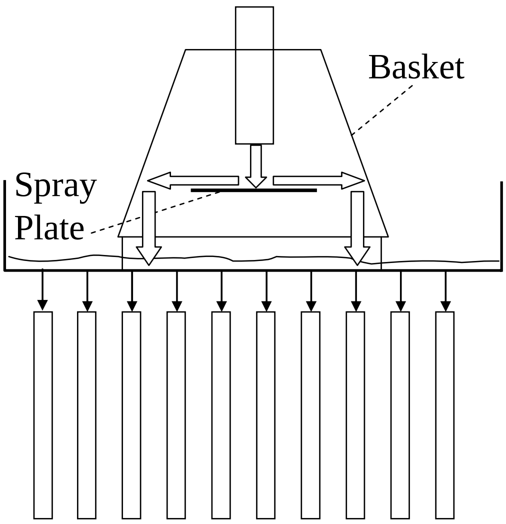


Figure 1-13: Niro evaporators use a spray plate and deflector basket to transfer the incoming liquid onto the distribution plate.

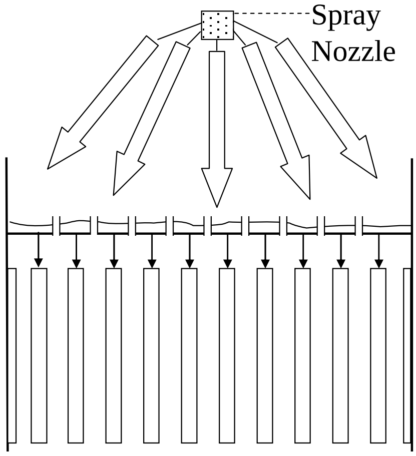


Figure 1-14: Stork evaporators spray liquid directly onto the distribution plate.

The liquid surfaces on the Niro distribution plates were not static but in constant motion. There was a circle below the circumference of the baskets, where the milk fell onto the distribution plate and then flowed sideways. Areas near the edge were expected to have stagnant amounts of liquid. Clearly, a low liquid head height was expected to cause uneven flows through the holes. The liquid head height should always be at least 20 to 30 mm. Below this, waves can form, stopping a coherent liquid head forming (Ken Morison, personal communication, 2004).

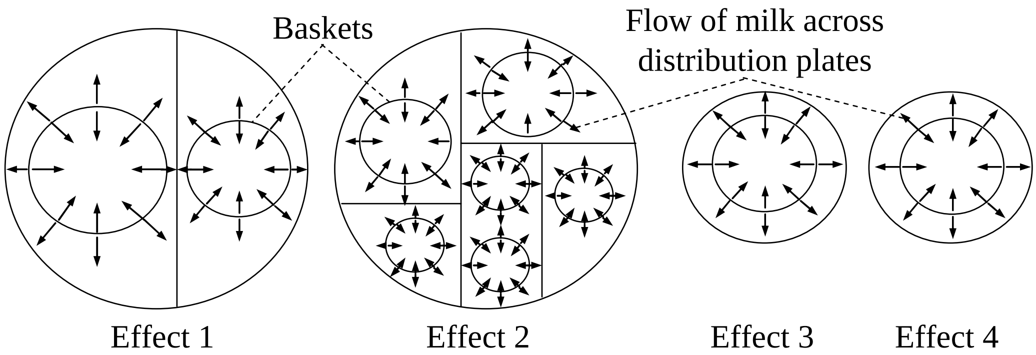


Figure 1-15: The flows of milk across the Niro distribution plates.

The Stork product distribution system was not expected to have such extreme sideways flows. the liquid head height for Stork evaporators was unknown. There may be a large force of impact for droplets hitting the liquid surface because of the height of the sprayer above the distribution plate. The droplet size will determine whether this is important or not. As Stork evaporators do not have viewing ports, it is unknown whether skim milks and MPCs foam significantly in these evaporators.

Viscous Fouling

A distributor cannot fully wet the tubes if there is insufficient liquid. There is a minimum wetting rate for a dry evaporator tube. Below this rate the tube cannot become fully wet.

If a tube is not fully wet, there will be dry patches which do not take part in evaporation. This reduces the evaporating area. Thin rivulets can flow down dry surfaces and they evaporate as they do so. Eventually they can become stationary viscous trickles which form *viscous fouling* on the tube surface. This is shown in Figure 1-16

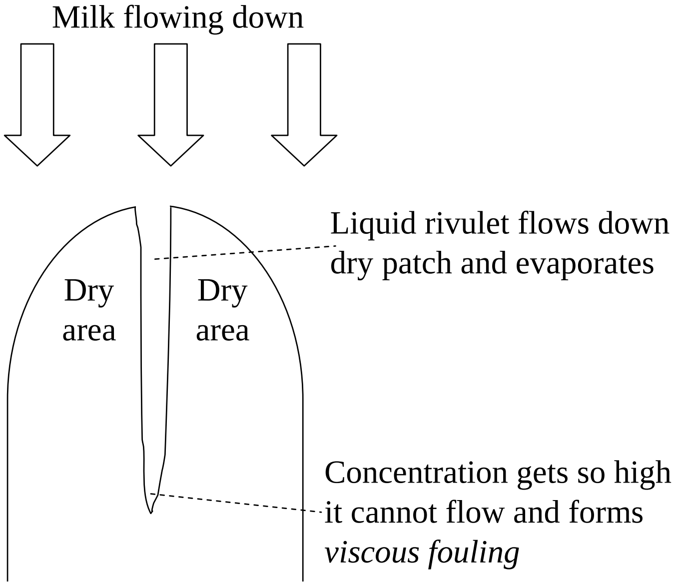


Figure 1-16: Thin rivulets flowing down dry patches can form viscous fouling.

Viscous fouling occurs at evaporator operating temperatures, between 75ºC and 48ºC. It is different to *heat transfer fouling*, which is caused by denatured proteins sticking to surfaces, and typically occurs at temperatures above 80ºC. Viscous fouling hardens and turns black with time. The tube can eventually block if the fouling is not removed.

Wetting Rates

Wetting rates must be evaluated at the point in a tube where there is the greatest chance of film break-up. The flowrate of milk decreases down the tube due to evaporation, so the wetting rates are the lowest at the base of the tube. The outlet wetting rate is defined by Equation 1. The variable $\dot{m}_{out}$ is the average outlet flowrate of milk from each tube and Γ_{out} is the wetting rate at the bottom of the tube.

$$\Gamma_{out} = \frac{\dot{m}_{out}}{\pi \, d_i \, n_{tubes}} \qquad \textbf{(1)}$$

Once a tube is fully wet by milk, it remains wet even when the flowrate is below the minimum required to wet a dry tube. A tube can remain wet at approximately half the minimum wetting rate for a dry tube, provided there is good liquid distribution (Robinson, 2004).

Equation 2 describes the heat transfer through the wall (Q) in terms of the overall heat transfer coefficient (U), evaporating surface area (A) and temperature difference (ΔT).

$$Q = UA\Delta T \qquad \textbf{(2)}$$

Flows in Evaporating Tubes

The evaporated water vapour exits the bottom of the tubes co-currently with the liquid. As evaporation occurs under a vacuum between 48ºC and 75ºC, the low operating pressures mean that the outlet vapour velocities become rather large. They can range from typically 10 to 30 m s^{-1} (for comparison, 36 to 108 km h^{-1}). Niro appears to use a constraint of minimum vapour velocity in its designs, as suggested by Niro’s Clandeboye Dryer 2 proposal (c. 2000).

Jebson and Iyer (1991) expect that the vapour velocity raises the heat transfer coefficient due to an increase in turbulence. They mention there should be a maximum acceptable limit to vapour velocity, above which liquid may be stripped off tube walls and evaporation is hindered. The mechanism for this flow is not given. In a personal communication, Ken Morison (2005) stated that “when the gas flow rate gets sufficiently high, the liquid will form an annulus on the tube wall and the gas will flow through.” The speed of sound in water vapour gives a velocity limit of 442 m s^{-1} at 50ºC and 474 m s^{-1} at 70ºC (de Nevers, 1991).

Distribution Plate Design Guidelines

There are no useful guidelines publicly available for the design of distribution plates. The required fundamental knowledge is either un-researched or confidential to companies. Useful information for distribution system design which is not readily available includes:

- The effectiveness of using three and six holes on forming liquid films in a dry evaporator tube.
- The optimum height of distribution plates above a tubesheet.
- The impact of vapour velocity and momentum from tubes on evaporation and falling film wetting.

1.1.7 Heat Transfer

Heat from condensing steam passes through many barriers before it can evaporate the milk. This section describes the mechanisms in detail.

Steam Quality

The steam must be saturated so that instantly condenses when it contacts the tube wall. Water is sprayed into the steam exiting the MVR fans to remove any superheat.

Non-Condensable Gases

Non-condensable gases present in water vapour can accumulate around the outside of the tubes and slow the condensation of steam, reducing the heat transfer rate (Mackereth, 1995, p. A33). The integrated preheaters on effects 1 and 2 act as condensers to remove non-condensable gases, as do the effect 3 preheaters when the evaporators are on MPC production. There are also deaeration lines for each effect which go to the condenser.

Modes of Steam Condensation

There are two modes of condensation: *drop-wise* and *film-wise*. Drop-wise condensation means steam condenses as droplets and trickles down the outside of the tubes. Film-wise condensation means steam condenses and flows down the tube as a film. This creates a barrier to heat transfer down the length of the tube, as heat must flow by convection through this layer. The stainless steel evaporator tubes undergo film-wise condensation.

Wall Conduction

The conduction of heat in stainless steel is low. The wall thickness of the evaporator tubes is approximately 1.245 mm, according to ASTM data from Mills (1999, p.942). There is a range of thermal conductivity values for of AISI 316 stainless steel. Webby (2002) gives a value of 13.4 W $m^{-1}K^{-1}$. Internet sources give values from 14.6 W $m^{-1}K^{-1}$ to 16.3 W $m^{-1}K^{-1}$. These are from the websites of www.egr.msu.edu (2005), www.assda.asn.au (2005), hcrosscompany.com (2005) and www.aksteel.com (2005). Copper has a much higher thermal conductivity of approximately 400 W $m^{-1}K^{-1}$ (www.efunda.com. 2005) but unfortunately is unsuitable for milk processing.

Fouling

Fouling can form on the outside and inside of the tubes. The outsides of the tubes are generally assumed to remain clean. The inside of the tubes are fouled by proteins and minerals which adhere to the surface. Fergusson (1989) reports a thermal conductivity of fouling as 0.3 to 3 $W\,m^{-1}K^{-1}$. This is likely to be for mineral fouling, which is sometimes called *milk stone*.

Boiling Point Elevation

Concentrated milk solutions can have a small boiling point elevation. This means the solution must become superheated in order to evaporate. This is governed by Equation 3, which is from Morison (unpublished).

$$\Delta T_b = \frac{-RT_{wb}^2 \ln a_w}{\Delta h_v} \tag{3}$$

Boiling point elevation is important for design calculations and explains the higher temperature differences in concentrate effects. It was not used for calculating the OHTC, as it requires the shell-to-effect temperature difference. For example, Mackereth (1995, p. A33) found a boiling point elevation of 0.75ºC for 40% skim milk.

Overall Heat Transfer Coefficient (OHTC)

The overall heat transfer coefficient is found from the total solids of milk entering and exiting a pass. The OHTC is described in Equation 4, and is based on the inside tube diameter, d_i. It is a modification of Equation 2.

$$U = \frac{\Delta h_v \, \dot{m}_{evap}}{\pi \, d_i \, L \, \Delta T} \tag{4}$$

The OHTC can be described in terms of three heat transfer resistances in Equation 5. These terms are the internal heat transfer coefficient (h_i), the ease of heat transfer through the wall (t/k_s) and the external heat transfer coefficient (h_o).

$$\frac{1}{U} = \frac{1}{h_i} + \frac{t}{k_s} + \frac{d_o}{d_i \, h_o} \tag{5}$$

The internal heat transfer coefficient describes the heat resistance of milk evaporating on the inside of the tubes, and the external heat transfer coefficient describes the heat resistance of steam condensing on the outside of the tubes. As the total solids of the milk increases through the evaporator, the internal heat transfer coefficient decreases, causing a corresponding drop in the OHTCs.

External Heat Transfer Coefficient

The external heat transfer coefficient describes the steam condensing on the outside of the tubes. Condensed steam flows down the tubes as a film. As the average film thickness of the condensate increases down the length of the tube there is more resistance to heat transfer, and the h_o lowers. S.L. Chen *et al.* (1987) provide Equation 7 which gives the average film heat transfer coefficient along the length of the tube, on the outside. The accuracy is claimed to be ± 10% of experimental results (Morison, unpublished).

$$h_o = k_l \left(\frac{g \rho_l^2}{\mu_l^2} \right)^{1/3} \left[\mathrm{Re}_L^{-0.44} + 5.82 \times 10^{-6}\, \mathrm{Re}_L^{0.8}\, \mathrm{Pr}_l^{1/3} \right]^{1/2} \quad \textbf{(6)}$$

Re_L is the dimensionless Reynolds number. It is found using Equation 8.

$$\mathrm{Re}_L = \frac{4\Gamma_L}{\mu_L} \quad \textbf{(7)}$$

The Γ_L is the wetting rate of the condensate at the bottom of the tubes on the outside. It is found using Equation 9. The $\dot{m}_{evap}$ is the mass of evaporation in the pass, which is virtually identical to the steam condensation rate.

$$\Gamma_L = \frac{\dot{m}_{evap}}{\pi\, d_o\, n_{tubes}} \quad \textbf{(8)}$$

Internal Heat Transfer Coefficient

The internal heat transfer coefficient (h_i) for a pass is found using Equation 6. This is a rearrangement of Equation 5, and requires the overall and external heat transfer coefficients to be known.

$$h_i = \frac{U\,k_s d_i\,h_o}{k_s d_i\,h_o - d_i\,h_o U\,t - U\,k_s d_o} \qquad \textbf{(9)}$$

Boiling Regimes

Incropera & DeWitt (1990) report a Nukiyama boiling curve for water at atmospheric pressure. This is shown in Appendix A-14. Convective boiling is surface evaporation where the heat is conducted through the product film. This happens with overall temperature differences below approximately 5ºC. Nucleate boiling begins for temperature differences above approximately 5ºC and involves the formation of bubbles at the wall, which grow and travel to the film-vapour interface. The heat transfer rate is higher for nucleate boiling, but the bubble formation tends to ‘dry out’ the wall surface, increasing the potential for fouling (Mackereth, 1995, p.A29).

The point at which convective film evaporation becomes nucleate boiling for milk is unclear. Müller-Steinhagen (1989) reports that the temperature difference required for nucleate boiling increases when the liquid is flowing over a surface and when the boiling temperature is reduced. This describes falling film evaporator operation very well. Billet (1989, p.139) reports that the temperature difference required for a falling film is 7ºC. Houšová (1970) shows the transition may occur at temperature differences of 10ºC. Bouman *et al.* (1993) claimed the onset of nucleate boiling occurred at approximately 0.5ºC across a boiling film, which probably gives a 1ºC to 2ºC overall temperature difference. More research is required.

1.1.8 Fouling

Fouling in the context of falling film evaporators is the deposition of matter onto evaporator surfaces. Fouling on the inside of the tubes is a particular concern, as it decreases the heat transfer area and provides sites for thermophilic bacterial growth. Currently, thermophilic bacterial growth restricts Clandeboye’s evaporators to a maximum of 20 hours operation (Richard Hickson, note to operators, 2005).

The most common way to measure fouling is to monitor increases in the temperature differences across each effect. The temperature differences rise when the heat transfer coefficients decrease, so that evaporation rates remain constant (Equation 2). To do this, the MVR fan speeds increase and the steam pressure for TVR effects increase.

This project took process data and total solids data from the evaporator to back-calculate the OHTC in each pass. This quantified the impact of fouling. However, this is not common practice in industry as it is time consuming and slow.

Cleaning of Evaporators

The New Zealand dairy industry takes cleaning very seriously. A full evaporator clean takes between three and four hours after every run. The general cleaning procedure is:

- Water rinse.
- Flush with caustic soda (sodium hydroxide).
- Recirculated wash with caustic soda.
- Water rinse.
- Recirculated wash with nitric acid.
- Water rinse.

Caustic soda removes proteins, and nitric acid removes the minerals from the surfaces. A considerable amount of time and energy is spent cleaning the evaporators. A cleaning cycle uses approximately NZ$700 worth of cleaning chemicals and utilities. The milk losses associated with start-up and shutdown are approximately NZ$200. (James Winchester, personal communication, 2005).

1.2 Minimum Wetting Rates from Literature

Tandon (2004) provides a comprehensive review of minimum wetting rates from literature. There was very little work available on the minimum wetting rates of milks.

1.2.1 Experimental Work

The authors in Table 1-5 experimentally measured the minimum wetting rate of skim milks and distilled water.

Table 1-5: Experimental measurements of the minimum wetting rates of distilled water and milks in initially dry tubes.

Author	Liquid Tested	Conditions

Paramalingam *et al*. (2001)	Skim Milk	Isothermal
Tandon (2004)	Distilled water, reconstituted skim milk (10% and 40%)	Isothermal and heat transfer
Riley (2004)	Distilled water, reconstituted skim milk (10% and 40%).	Isothermal and heat transfer.
Robinson (2004)	Distilled water, reconstituted unstandardised skim milk.	Fouling due to incomplete wetting for skim milks.

Isothermal conditions were when the milk at 60ºC flowed with negligible heat transfer down a heated tube at 60ºC. Heat transfer conditions involved sending 60ºC milk down a 65ºC heated tube, giving heat transfer into the milk.

Paramalingam *et al.* (2001) measured the contact angles of skim milk and used correlations from Hartley and Murgatroyd (1964) and Hoke and Chen (1992) to calculate the minimum wetting rates.

Tandon (2004) and Riley (2004) investigated the minimum wetting rates of reconstituted unstandardised skim milk and distilled water. This was done on the 'Wetting Rig' at the Department of Chemical and Process Engineering, in the University of Canterbury. This investigated various methods of liquid distribution and took some wetting rates under isothermal, heat transfer and evaporation conditions.

Robinson (2004) investigated the fouling of evaporator tubes. This was for dry and for previously wet tubes. The milk concentrations varied from 10% to 60%. The key finding was that previously wet tubes with good distribution, which had been dried but not cleaned, could be re-wet at a wetting rate of 0.054 kg $m^{-1}s^{-1}$. Clean dry tubes would fully wet between approximately 0.1 kg $m^{-1}s^{-1}$ and 0.2 kg $m^{-1}s^{-1}$.

There has been no literature found for whole milk or MPCs.

1.2.2 Theoretical Minimum Wetting Rates

Much of the work on minimum wetting rates is based on the contact angle. This measurement is the angle formed between the edge of a droplet and the surface on which it sits. The contact angle is illustrated in Figure 1-17.

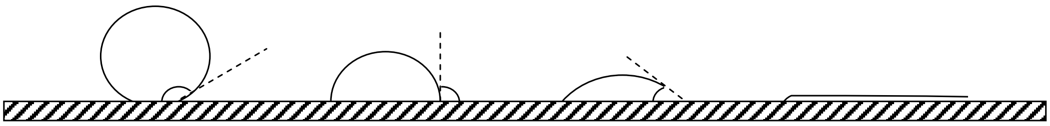


Figure 1-17 Contact angles and spreading of a drop.

Table 1-6 details authors who have developed relevant correlations for the wetting of a dry surface by a laminar film flowing under gravity. This list is compiled from Tandon (2004). No equations were particularly useful for predicting the minimum wetting rate of milks. Further experimental measurements were required.

Table 1-6: Theoretical correlations developed for the minimum wetting rates of liquids on initially dry surfaces.

Author	Equation	Comments
Hartley and Murgatroyd (1964)	$\Gamma_{min} = 1.69\left(\frac{\mu_l \rho_l}{g}\right)^{1/5}\left[\sigma_l\left(1-\cos\theta\right)\right]^{3/5}$ **(10)**	Isothermal conditions. Overestimation of minimum wetting rate for water, sucrose and milk.

Hobler (1964)	$$\Gamma_{\min} = 1.5788\left[\sigma_l\left(1-\cos\theta\right)\right]^{3/5}\left(\frac{\mu_l \rho_l}{g}\right)^{1/5} \quad \textbf{(11)}$$	Isothermal.
Zuber and Staub (1966)	$$\frac{\rho_l}{15}\left[\frac{g\left(\rho_l-\rho_v\right)}{\mu_l}\right]^2 \delta_{\min}{}^4 = \frac{\sigma_l\left(1-\cos\theta\right)}{\delta_{\min}} +$$ $$(\gamma)\frac{\mathrm{q/A}}{\mathrm{k}_l}\cos\theta + \rho_v\left[\frac{\mathrm{q/A}}{\rho_v \Delta h_v}\right]\frac{\left(\rho_l-\rho_v\right)}{\rho_l}\cos^2\theta \quad \textbf{(12)}$$ $$\Gamma_{\min} = \frac{\delta_m{}^3 g\left(\rho_l-\rho_v\right)^2}{3\mu_l} \quad \textbf{(13)}$$	Heat Transfer for water.
Ponter, Davies, Boss and Thornley (1967)	$$\Gamma_{\min} = 1.12\left(\sigma_l\left(1-\cos\theta\right)\right)^{3/5}\left(\frac{\mu_l \rho_l}{g}\right)^{1/5} \quad \textbf{(14)}$$	Isothermal.
Doniec (1984, 1988, 1991)	$$\Gamma_{\min} = 1.0179\left(\frac{\rho_l \mu_l}{g}\right)^{1/5}\left(\sigma\left(1-\cos\theta\right)\right)^{3/5} \quad \textbf{(15)}$$	Isothermal.
Hoke and Chen (1992)	$$\sigma\left[1-\cos\theta\right] = \frac{\rho_l g}{4}\left[\frac{\delta_{\min}}{1-\cos\theta}\right]^2$$ $$\left[2\theta-\sin\left(2\theta\right)\right] + \frac{\rho_l{}^3 g^2 (\delta_{\min})^5}{15\mu_l{}^5} \quad \textbf{(16)}$$ $$\Gamma_{\min} = \frac{\rho_l{}^2 g\left(\delta_{\min}\right)^3}{3\mu_l} \quad \textbf{(17)}$$	Isothermal.
Tandon (2004)	$$\Gamma_{\min} = 3.80\mathrm{x}10^5\ \mu_l{}^{0.24}\ \rho_l{}^{-1.66}\left(\sigma\left(1-\cos\theta\right)\right)^{3/5} \quad \textbf{(18)}$$	Isothermal. Good for sugar and water, but not for milk.

1.3 Project Objectives

The specific goals of the project were as follows:

- To determine the current operating conditions for Clandeboye's milk evaporators. The focus was on the wetting rates, heat transfer coefficients and fouling rates.
- To relate the operating conditions to minimum wetting rate equations from Tandon (2004) and minimum wetting rate measurements.
- To determine the effectiveness of the current liquid distribution systems.
- To identify evaporator passes with poor wetting rates and determine the improvements that can be made to the worst case, estimating the benefits available of such improvements.
- To develop new design and retrofit guidelines for liquid distribution systems in falling film evaporators, and identify any other operating issues that affect liquid distribution.

The rest of this thesis shows how this work was done, the results from the investigations and the importance and implications of the findings.

2. Materials and Methods

2.1 Overview

This section gives an overview of the various investigations made on the evaporators.

- The minimum wetting rates of milk in a dry evaporator tube were found for reconstituted skim milk, whole milk and milk protein concentrate with an 85% dry basis protein content (MPC-85). The measurements covered a variety of heating conditions and milk concentrations, and were used to evaluate the performance of the evaporators. (Section 2.2)

- Logbooks for the 2003-2004 milk powder season were analysed to find the average run length for skim milk, whole milk and milk protein concentrates (MPCs). (Section 2.3)

- Milk samples from each pass were analysed for their total solids contents. Combined with process variables from the company process database, this enabled steady state models of the wetting rates and heat transfer coefficients in the evaporators. (Sections 2.4 to 2.6)

- An iterative method in Excel calculated the pressure drop down tubes in each pass. (Section 2.7)

- Physical measurements were made of the distribution section for every evaporator at Clandeboye. The general design of the distribution section was investigated and checked for faults. The evaporators at Fonterra Edendale were also measured. (Sections 2.8 and 2.9)

- The flows of liquid from the holes in the distribution plate to the tubes were analysed theoretically, and a water trial measured the flows from each tube to find the uniformity of flows. (Sections 2.10 and 2.11)

- Photographs were taken of the evaporators after operation but before cleaning for whole milk and MPC-85. (Section 2.12)

2.2 Single Tube Minimum Wetting Rate Measurements

2.2.1 Background

Measurements of the minimum wetting rates for water and milks were performed under isothermal, heat transfer and vacuum evaporation conditions in the *Wetting Rig*, located in the Department of Chemical and Process Engineering at the University of Canterbury.

The purpose of the wetting rig was to mimic start-up conditions in evaporators. 'Start-up' involved feeding the evaporator with water. The purpose is to wet the tubes and avoid 'hot patches' forming in the tubes, which can cause fouling when milk flows over the surfaces. When production begins the water is replaced with milk.

At the beginning of start-up, a dry evaporator tubes must become wet with water, hence the need to find the minimum wetting rate for water in a dry tube. It was expected that a tube fully wet with water would remain wet when the fluid became milk.

Water has a much higher heat transfer coefficient than milk, so during start-up most water was expected to evaporate before it reached the final passes. This was observed and it was doubtful that the tubes were fully wet with water. The transition from water to milk, with its lower heat transfer coefficient, would mean a dry evaporator tube would become wet with milk. This is why the wetting rig was used to mimic the process of wetting a dry evaporator tube with milks of various concentrations.

The wetting rig consisted of a 2 inch AISI 304 vertical stainless steel evaporator tube, surrounded by a water jacket. Experiments were performed across eight weeks from October to November 2004. This was for dilute and concentrated solutions of reconstituted skim and whole milks, and MPC-85. Table 2-7 details the measurements made.

The skim milk was non-instant skim milk produced at Fonterra Clandeboye in CD2 on 19 October 2003, specification 20-0015. The dry basis composition was 54.0% lactose, 32.7% protein, 7.8% minerals, 4.9% moisture and 0.6% fat. The heat treatment was 3-step with a 99ºC DSI temperature and a 10 second holding time.

Table 2-7: Minimum wetting rate measurements for skim and whole milks and MPC-85 for a single dry evaporator tube.

Condition	Milk Types	Conditions
Isothermal	Skim and whole milks MPC-85	10% and 40%TS at 60ºC 10% and 24% TS at 60ºC
Heat transfer	Skim and whole milks MPC-85	10%, 40% and 50%TS at 60ºC 10% and 24%TS at 60ºC
Evaporation	Skim and whole milks MPC-85	10% and 40%TS at 60ºC 10% and 22% TS at 60ºC

The whole milk was cypher JO24, specification 22-0027, made on 24 May 2004 in CD1. This had a 3-step heat treatment, 10 seconds holding time, and a 90ºC DSI temperature. The typical dry basis composition was 26.8% fat, 3.2% moisture, 24.8% protein, and 45.2% combined lactose and minerals.

The MPC-85 was cypher HO11, specification 66-4854, made in CD2 on 11 March 2004. It had an approximate dry basis composition of 1.8% fat, 6.9% moisture, 81.0% protein, 3.2% lactose and 7.1% minerals.

2.2.2 Physical Construction of Wetting Rig

The wetting rig consisted of a vertical evaporator tube and ancillary equipment. A 6 L tank was filled with between 2 L and 3 L of milk. The process liquid will be referred to as milk although it was sometimes distilled water. More information is available from Riley (2004).

A Micropump 120 series gear pump, controlled by variable speed drive, allowed very small changes to the gear pump speed using a 10 turn potentiometer. The pump was built by Industrial Parkway South which is located at Aurora, in Ontario, Canada.

The pump extracted milk from the tank, passing it through preheating coils and a rotameter. The preheating coils were immersed in a water bath. The bath had a Grant electronic temperature controller to maintain the temperature. The milk line was lagged 9.5 mm diameter stainless steel tubing. A bypass line sent the milk back to the tank until it was heated to the desired temperature.

The vertical evaporator tube was 1 m tall and constructed from AISI 304 stainless steel. A distributor transferred the milk to the inside of the tube at the top. The distributor was non-glazed ceramic tube with an inner diameter of 47.6 mm. The top was perfectly flat with rounded edges to allow milk to overflow from the outside of the distributor to the inside as a coherent film. A perforated nylon ring was attached to the outside of the distributor to give a uniform liquid flow around the circumference of the distributor, and to hold it in place. Figure 2-18 shows the distributor.

A water jacket with a 72 mm outer diameter surrounded the evaporator tube. A Wilo Star RS25/6 centrifugal pump sent water from a heated bath to the bottom of the jacket annulus through 25 mm diameter pipes. The water exited the top of the jacket and poured back into the bath. An electronic temperature controller was used to maintain a steady water temperature. A second heater was added when the tube was under evaporation conditions to provide extra heating. The heat flux was approximately 1650 W $m^{-2}K^{-1}$ (Riley, 2004, p.29). This is comparable to an industrial evaporator.

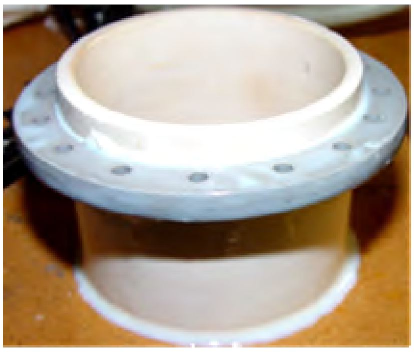


Figure 2-18: The non-glazed ceramic distributor used, with its attached nylon ring for positioning.

The tube wetting for isothermal and heat transfer conditions was observed by looking down the evaporator tube. The top was sealed when the system was under vacuum for evaporation conditions. This made inspection more difficult. A glass tube was sealed into the centre of the evaporator tube. It was 1.5 m long with an outer diameter of 28 mm, and it had a 2 mm wall thickness.

A Swann ‘Spy Cam’ mini video camera was inserted down the glass tube to inspect the tube wetting, and the image was projected onto a television screen. This allowed inspection of the inside of the evaporator tube. A hairdryer was attached to the bottom of the glass tube to prevent condensation on the glass walls. The picture became fuzzy when the Spy Cam was above 40ºC so a second hairdryer was used to periodically cool the Spy Cam. The tube had to be inspected down the entire length to ensure that full wetting was achieved.

2.2.3 Process description

Previous calibration work by Tandon (2004), Riley (2004) and Robinson (2004) determined the required temperatures and flowrates for effective operation of the wetting rig. This was under isothermal, heat transfer and vacuum evaporation conditions.

The milk temperature was set at 60ºC. Isothermal conditions involved having negligible heat transfer across the tube wall. This meant the water jacket was at the same temperature as the milk. Heat transfer conditions involved having the water jacket hotter than the milk, giving an overall temperature difference of 5ºC across the tube wall. Isothermal and heat transfer runs were performed at atmospheric pressure.

Evaporation conditions involved operating at the 60ºC saturation pressure and maintaining a 5ºC temperature difference with the water jacket. The difference between the local atmospheric pressure and the wetting rig pressure was measured using a manometer. A spreadsheet was used to determine the mercury height required for the saturation pressure at 60ºC.

While the system was approaching steady state, the gear pump was set to maximum speed of 2200 rpm and the milk was recirculated into the tank until the milk was at the desired temperature. At steady state the pump speed was decreased to 700 rpm and the milk sent to the distributor instead of the bypass line. The ceramic distributor wet more readily than the tube so the distributor was completely wet before the tube. Approximately 3 mm of the tube was fully wet at the top, but the film broke below this height into rivulets.

The wetting rate was increased by slowly raising the pump speed in increments of 50 rpm per minute until it was nearly fully wet. The increment size was then reduced to 20 rpm per minute until the evaporator tube became fully wet. Extreme care was taken not to shake the rig, which could disrupt the liquid film. The rotameter level was then recorded and the milk diverted to the recirculation line. A flexible hose was removed from this line to measure the mass flowrate of the milk.

A stopwatch, beaker and scales accurate to ± 0.01 g were used for calculating the flowrate and wetting rate. The total solids content of the milk was measured using the procedure from Riley (2004). Total solids testing was particularly important when the wetting rig was under evaporation conditions, as the concentrations increased over time.

Liquid remained in the coils after the tank had been drained. A glass catch pot system was connected to the house vacuum and it sucked leftover liquid from the pipework. It also removed liquid after cleaning cycles and drained the system at the end of the day.

Distilled water, aqueous 2% sodium hydroxide and 2% nitric acid were used to clean the apparatus after each experimental run. This took approximately two hours. See Riley (2004) for further information.

Figure 2-19 shows the single tube wetting rig with some of its associated parts.

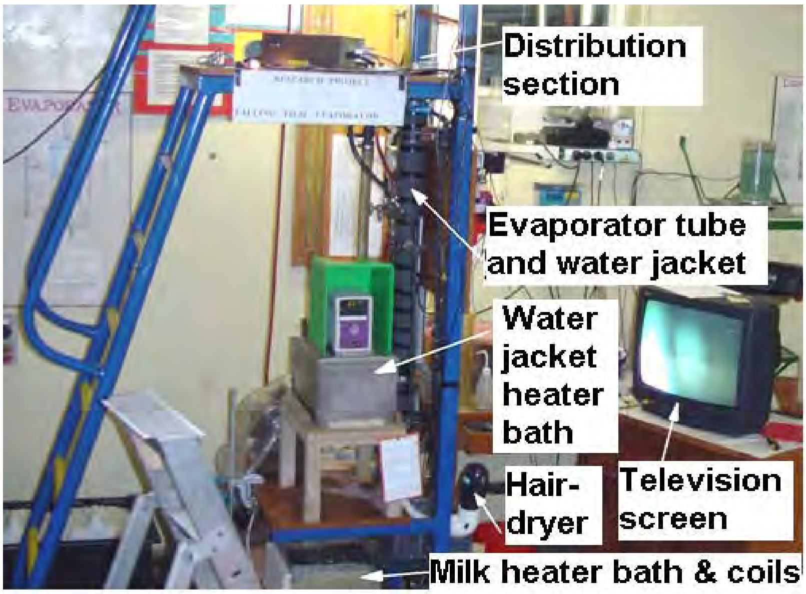


Figure 2-19: The single tube wetting rig in the Department of Chemical and Process Engineering at the University of Canterbury.

2.3 Logbooks

This project required the average evaporator run length for each milk type during the 2003-2004 milk powder season.

The run lengths were analysed from CD1 and CD2 evaporator logbooks. The evaporators processed skim and whole milks, MPC-70 and MPC-85. An Excel spreadsheet recorded information on the evaporator use during the season. This covered which evaporators were running, the milk being processed, when the evaporators were cleaned or on standby and which dryer they were feeding. The run lengths for each milk type were displayed on histograms.

2.4 Measurement of Fouling

Fouling can be monitored several ways and it causes the OHTCs in a pass to drop. Taking total solids samples and calculating the OHTC is the most accurate way to measure fouling. Unfortunately this is slow and is not common practice.

An increase in the temperature difference across an effect indicates the formation of fouling. The MVR fan speeds and the TVR steam pressure must increase to create a larger temperature differences.

In practice, the MVR fan speeds and temperature differences were an excellent indicator of fouling in effects 1 and 2. The TVR section was difficult to monitor. The uncertainty of total solids tests increased at high solids concentrations. The most reliable method to find fouling in the TVR section was to open the evaporator up before cleaning. This was useful but not often very practical.

2.5 Total Solids Testing

Equations 1 to 4 and 20 to 24 were used to calculate the outlet wetting rates and OHTCs for each pass. Milk samples were taken from points at the outlet of each pass, when the evaporators were at steady state.

The in-process powder plant laboratory held refractometer and a MilkoScan, which was a FOSS milk analyser. These gave useful approximations for the total solids concentrations of the milks.

The Clandeboye Site Laboratory analysed the samples for total solids contents. The Clandeboye total solids procedure appears in Appendix A-8. It involved drying 3 g of milk or 1 g of milk concentrate (milk above 20% TS) for four hours in an oven at 105ºC. The results were retrieved from the LabPro computer program.

Samples were stored in the lab chiller between 3ºC to 6ºC until testing, which happened in the next immediate morning and afternoon. Tuesday was the laboratory's calibration day, so there were no tests. Samples could be held for up to 36 hours before testing.

Table 2-8 shows the total solids sample points available in each evaporator. Most total solids samples were from Evaporators 1 and 4. This was because these evaporators had enough sample points to calculate the OHTCs for every pass. It took up to 10 minutes to collect the set of milk samples. There was no sample point in the outlet of Evaporator 1 effect 3. The assumption of equal evaporation rates between effects 3 and 4 gave an approximate total solids value.

Table 2-8: The sample points available for milk sampling in Evaporators 1 to 5.

Evaporator	**Sample Points on Outlet of:**				
	Feed	**Effect 1**	**Effect 2**	**Effect 3**	**Effect 4**
1	Balance tank	Passes 1 and 2	Passes 1 to 5	None	Outlet
2	Balance tank	None	Pass 5.	None	Outlet
3	Balance tank	Pass 2	Pass 5	Outlet	Outlet
4	Balance tank	Passes 1 and 2	Passes 1 to 5	Outlet	Outlet
5	Balance tank	Pass 2	Pass 5	Outlet	Outlet

The laboratory had a standard for the accuracy of total solids tests. Duplications of the same samples had to agree within certain limits. Milk was classified as liquid with total solids contents less than 20% TS, on a mass basis. This is a mass fraction of 0.20 TS. Milk with a total solids concentration of 20% TS or more was classed as concentrate.

Duplicate milk samples had to agree to ± 0.10% TS. Milk concentrate samples had to agree to ± 0.30% TS. MPC samples had to agree within ± 0.30% TS. In practice, milk samples had excellent repeatability. MPC concentrate samples and skim and whole milk concentrates from effects 3 and 4 had uncertainties up to ± 1% TS.

2.6 Process Data and Steady State Model of Evaporators

Process data was available from Fonterra’s Mercury network which held information for six weeks. The InTouch control program sometimes provided outdated data.

The process data and the total solids results were used to create a steady state model of the heat and mass flows inside the evaporators. This was done for each evaporator and milk type. All the process variables were recorded between the start and end of the milk sample collection. The average values were calculated and the uncertainty was determined as twice the standard deviation during the sample period. Table 2-9 shows the inputs and the equations used.

Physical properties of milk and water were calculated using correlations in Visual Basic from Ken Morison (personal communication, 2004). The computer code and calculation procedures appear in Appendix A-10.

2.7 Pressure Drop down Tubes

Equation 25 was used to calculate the pressure drop down the tubes in each pass due to evaporation (Holland and Bragg, 1995). The sensors for the effect pressures and temperatures were at the bottom, near the vapour separator. This meant the pressure at the top of the liquid distribution section was unknown. A pressure was guessed at the top of the liquid distribution section in each pass and the pressure drop was calculated, giving the pressure at the bottom of the pass. Microsoft Excel Solver was used to converge the calculated and measured pressures at the bottom by changing the guessed pressure at the top of the pass. Refer to Appendix A-12 for the full iterative procedure.

$$-\frac{dP}{dx} = \left(\frac{2\,fG^2 v_v}{D} + 2v_v G\left(\frac{4U\Delta T}{D\Delta h_v}\right) + \frac{g}{v_v} \right) \Bigg/ \left(1 + G^2\,\frac{dv_G}{dP}\right) \quad \textbf{(25)}$$

The most reliable total solids results for skim and whole milks were from Evaporator 4. The MPC pressure drops were not reliable. The Evaporator 1 results did not give accurate pressure drops.

Table 2-9: The data used for creating the steady state spreadsheet models of the evaporators. This includes the input data, the constants, the computer program data and the calculated variables. The relevant equations are provided.

Data	Variables	Source	
Input data	Feed Flows	Sensors from process database	
	Temperatures	Sensors from process database	
	Pressures	Sensors from process database	
	Densities	Sensors from process database	
	Errors were 2* standard deviation in sampling time period.		
Constants	Number of tubes	Counted	
	Number of holes	Counted	
	Diameter of holes	Measured	
	Surface area of tubes	$A = \pi\, d_i\, L\, n_{tubes}$	**(19)**
Computer program data	Enthalpies of vaporisation	Computer program	
	Specific heat capacities, Cp	Computer program	
	Dynamic viscosities	Computer program	
	Vapour density	Computer program	
	Vapour pressure	Computer program	
		From Morison (personal communication, 2004).	
Calculated variables	Temperature difference	$\Delta T = T_{shell} - T_{effect}$	**(20)**
	Average total solids	$TS_{av} = \dfrac{TS_{in} + TS_{out}}{2}$	**(21)**
	Internal flows out	$\dot{m}_{out} = \dfrac{TS_{in}\, \dot{m}_{in}}{TS_{out}}$	**(22)**
	Evaporation rates	$\dot{m}_{evap} = \dot{m}_{in} TS_{feed} \left(\dfrac{1}{TS_{in}} - \dfrac{1}{TS_{out}} \right) - \dot{m}_{flash}$	(23)
	Flashing	$\dot{m}_{flash} = \dot{m}_{in} \dfrac{TS_{feed}}{TS_{in}} Cp_{milk} \left(T_{effect} - T_{enter} \right)$	**(24)**
	Overall Heat Transfer Coefficient	$U = \dfrac{\Delta h_v\, \dot{m}_{evap}}{\pi\, d_i\, L\, \Delta T}$	**(4)**
	External Heat Transfer Coefficient	$h_o = k_l \left(\dfrac{g \rho_l^2}{\mu_l^2} \right)^{1/3} * \left[Re_L^{-0.44} + 5.82 \times 10^{-6}\, Re_L^{0.8}\, Pr_l^{1/3} \right]^{1/2}$	**(6)**
	Outlet Wetting Rate	$\Gamma_{out} = \dfrac{\dot{m}_{out}}{\pi\, d_i\, n_{tubes}}$	**(1)**

2.8 Physical Measurements

Physical measurements were made of the liquid distribution systems to compare the evaporators. Measurements were made in each pass of the Clandeboye and Edendale evaporators. These included the hole sizes and numbers, the tube sizes and arrangements, the positioning of holes around tubes, checking for misalignment and warping, and the distribution plate dimensions.

The equipment used was very simple, as explained in Table 2-10. The callipers were equipped with a vernier scale and a depth gauge.

Table 2-10: Equipment used in taking physical measurements of the evaporators.

Equipment	Measuring limits and uncertainty
Digital camera	N/A
Tape measure	5 m ±1 mm.
Metal ruler	300 mm ±0.5 mm calibrations.
Mitutoyo Vernier callipers	250 mm vernier callipers ± 0.02 mm.

2.9 Edendale Trip

A trip occurred between 12 and 16 July 2004 to investigate the evaporators in the Edendale ED2 and ED3 plants. Measurements were taken for the numbers of holes and tubes in each pass and for the hole sizes. The arrangements of the tubesheets were investigated, particularly in effects 3 and 4. The distribution plates were investigated for any faults, warping and hole misalignment.

The logbooks were inspected to find the general operating conditions of the evaporators for skim and whole milks. Staff were asked about any instances of blocked evaporator tubes, the general running conditions and performance.

Table 2-11 shows the measurements made in the evaporators and the equipment used.

Table 2-11: Measurements made of the evaporators and the equipment used.

Measurement	Equipment and Methods
Tube & hole numbers	Counted tubes and holes by eye. Took photos of each pass when possible as a reference.
Hole sizes	Vernier callipers were used for measuring hole sizes.
Warping	The vernier calliper's hole depth gauge measured the vertical distance from the tubesheet to the top of the distribution plate. Warped plates had uneven heights above the tubesheet.
Misalignment	Used vernier calliper's hole depth gauge to estimate the angle from the edge of each hole to the nearest tube. Different angles indicated warping.

2.10 Holes-Tubes Analysis

The flow of liquid into a tube depends on the configuration and size of the holes surrounding it. The *holes-tubes* analysis calculated the amount of liquid entering the tubes. Niro distribution plates surround every tube with three holes at 120º intervals. Liquid from each hole flows to three tubes, as shown in Figure 2-20. Holes positioned at the edge of the tubesheet may only feed two tube or one tube, as shown in Figure 2-21 and Figure 2-22. This means half or even all of the flow from a hole can go to the nearest tubes or tube.

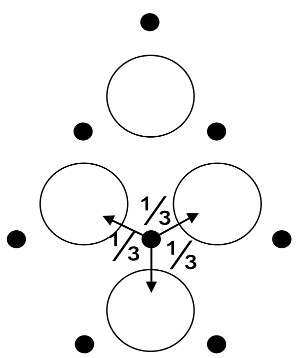


Figure 2-20: This hole feeds three tubes, splitting its flow three ways.

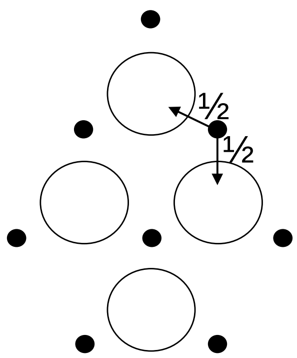


Figure 2-21: This hole feeds two tubes, giving each tube half its flow.

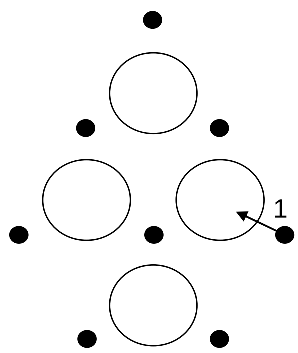


Figure 2-22: This hole feeds all its liquid to one tube.

When the holes are all the same size, tubes can receive different amounts of liquid, depending on their position in the tuhesheet. Figure 2-23 illustrates how tubes at the edge of a tubesheet can receive more liquid than those in the centre. A perfect distribution can be achieved by carefully designing the size of the holes.

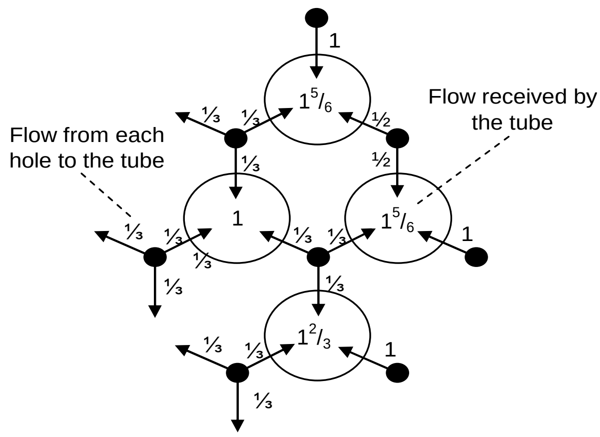


Figure 2-23: The misdistribution that can develop when equally-sized holes feed different numbers of tubes. The number "1" is the flow through one hole.

2.11 Wetsuit Job

2.11.1 Background

The holes-tubes analysis showed that tubes around the edge of passes received more liquid than those nearer the centre. A water trial was conducted on effects 3 and 4 of the evaporators. This was to determine whether there was a misdistribution of liquid. The actual flowrates into the tubes in effects 3 and 4 were measured while the evaporator was not running. This was done for the Niro distribution plates and with model distribution plates which were designed to give a perfect liquid distribution. This trial was quickly nicknamed the *wetsuit job* for obvious reasons.

2.11.2 Tube Fittings

Specially designed tube fittings allowed the measurement of the flow of water exiting the evaporator tubes. Holes were drilled through conical rubber bungs, which had a maximum diameter of 50 mm. Lengths of rubber hoses were glued into these holes. Figure 2-24 shows the assembly of the bungs and Figure 2-25 shows how they fitted into the tubes, capturing all the water exiting the tubes.

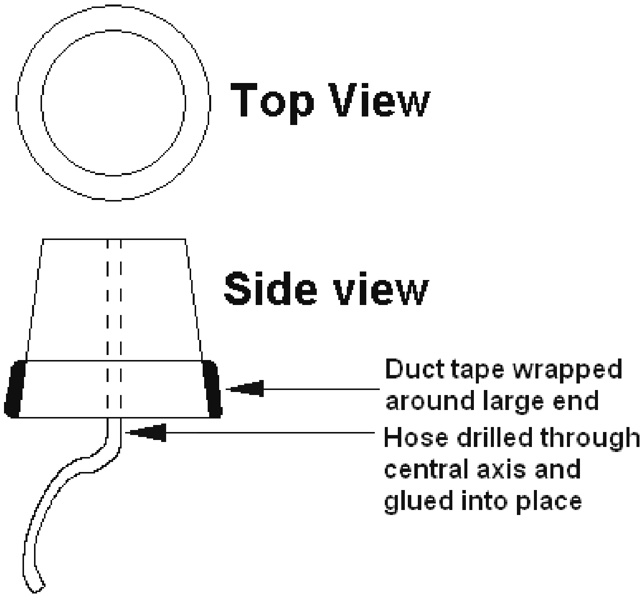


Figure 2-24: Construction of rubber bungs.

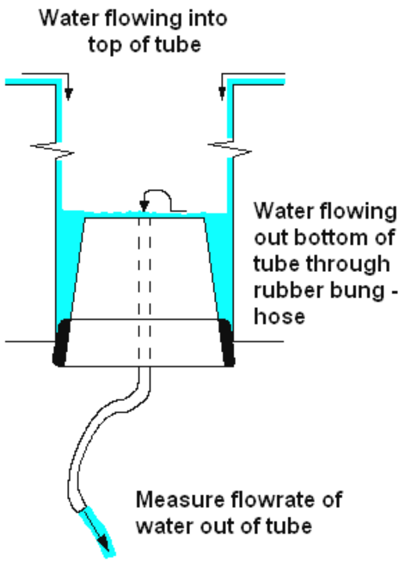


Figure 2-25: The bungs fitted into the bottom of the tubes, capturing the water.

2.11.3 Acrylic Distribution Plates

Model distribution plates were designed for effects 3 and 4 of Evaporator 4. These were made from 6 mm acrylic which was purchased from PSP Ltd in Christchurch. The metal thickness of the Niro distribution plates was 5.0 mm. Figure 2-26 shows one of the acrylic distribution plates.

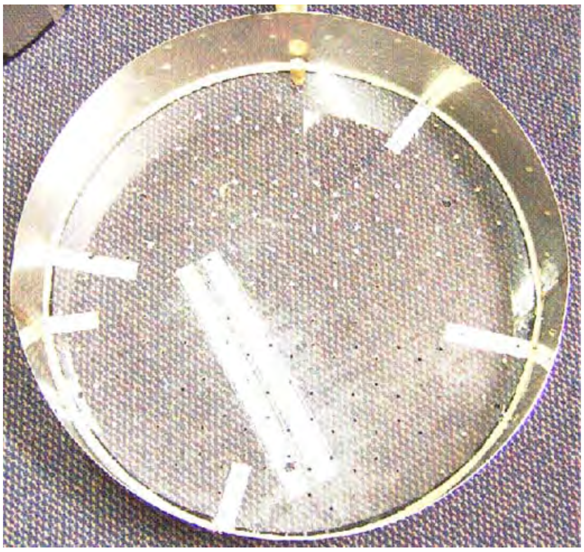


Figure 2-26: Acrylic distribution plate.

A six hole design was used with the intention of giving a uniform liquid distribution. The hole positions were traced and drilled onto the acrylic. The hole diameters were sized according to the number of tubes they fed. The hole sizes appear in Table 2-12. The combined area of all the holes was the same as for the Niro plates so that the liquid head heights would be the same.

Table 2-12: Hole sizes used for acrylic distribution plates

Number of tubes a hole fed	Effect 3 Hole Size mm	Effect 4 Hole Size mm
3	6.4	5.8
2	5.2	4.8
1	3.7	3.4
Niro plate	8.0	7.0

Stainless steel sheets were bent and welded into a circle, to provide the sides of the distribution plate. Metal supports, Fosroc professional silicone bathroom sealant and duct tape were used to seal the metal circle and acrylic plate together.

2.11.4 Experimental Procedure

Figure 2-27 shows the general experiment set-up.

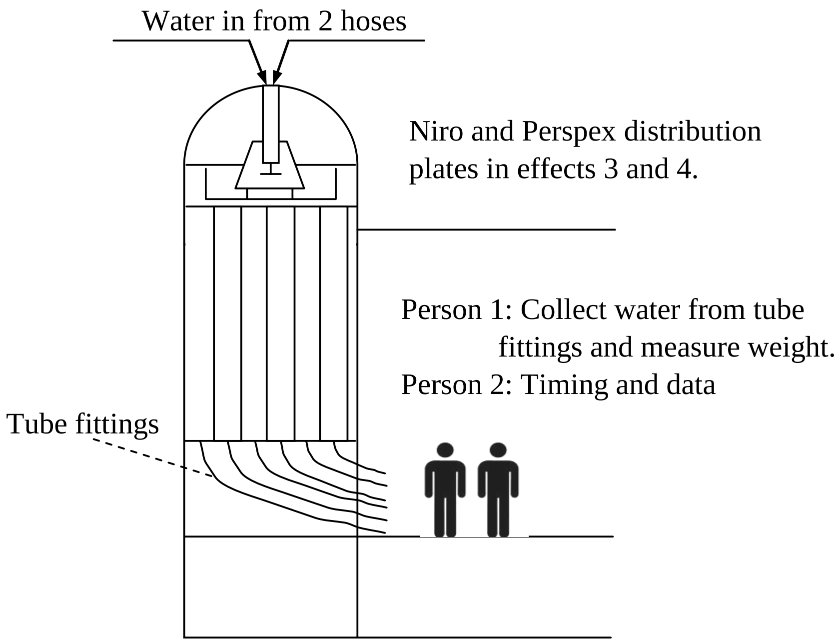


Figure 2-27: General set-up of the wetsuit job.

The pumps at the bottom of the effects were disconnected so that water could flow to the drain. The bungs were fitted into specific tubes at the bottom of the evaporator. The desired distribution plate was fitted into the effect. Bung fitting number 5 broke because of rough handling.

The flowrates of the two cold water hoses were measured at the start of the trial. Water was poured for 3 seconds into a bucket from each of the hoses. The mass of water was recorded by pouring it into the measuring container and weighing the contents on the digital scales. Since the evaporator was not operating, the flowrates of water entering and exiting the tubes were equal. Table 2-13 shows the inlet water flowrates.

Table 2-13: The inlet flowrates from the two hoses.

Hose	Total mass water ± 30 g	Total time ± 0.5 s	Flowrate kg s^{-1}	Uncertainty ± kg s^{-1}
1	2330	3.0	0.78	0.14
2	1950	3.0	0.65	0.12

The combined flowrate from the two hoses was 1.4 kg s^{-1} and was too low to form a liquid head. A typical concentrate flow is 3.0 kg s^{-1}. Half the holes in the distribution plates were blocked using rubber stoppers and Blu-tak. This gave a small liquid head height and the tubes that received liquid had typical wetting rates.

Table 2-14 lists the equipment used in the wetsuit job, its accuracy and purpose.

Table 2-14: Equipment used for the wetsuit job.

Equipment Used	Accuracy	Purpose
Bung Fittings	–	Collected water from tubes.
Stopwatch	± 0.1 s	Flowrate timing, done by the scribe.
Waterproof digital scales	± 5 g	Measured the outlet flowrate from tubes and the inlet flowrate from water hoses.
Container for water	255 g	Pre-wet weight of container.
Bucket	–	Collected flowrate of water from hoses.

One person filled a container with water from the bung fittings for approximately 15 seconds. Waterproof digital scales measured the initial and final masses of the container. The second person recorded data and used a stopwatch to record the time intervals. Three replications were made of flowrates exiting each tube. Figure 2-27 shows the general set-up of the investigation. Figure 2-28, Figure 2-29 and Figure 2-30 show the tubes which were sampled, marked with triangles. The view is from the bottom of the tubesheet. Sixteen tubes were blocked in effect 4 when using the acrylic distribution plate.

Figure 2-28: Tubes measured in effect 3 for the Niro and acrylic distribution plates.

Figure 2-29: Tubes measured in effect 4 for the Niro distribution plate.

Figure 2-30: Tubes measured in effect 4 for the acrylic distribution plate. Sixteen tubes were blocked.

2.12 Photos and Observations

Digital cameras were used to take photos on many occasions. Photos were taken of the evaporator tubesheets, distribution plates and fouling in the evaporator tubes.

Evaporators 1 and 2 were inspected after a 22 hour whole milk run on 26 May 2004 before cleaning. This was for non-instant whole milk, specification 22-0027, cypher JO25. It had a 90ºC, 3-step heat treatment for 10 seconds.

Evaporator 4 was opened after a 5 hour-long MPC-85 run on 5 April 2005 before cleaning. This was for specification 66-4853, cypher IP04. It had a 70ºC single-step heat treatment and 10 seconds holding time. The dry basis composition of the powder was less than 5.0% lactose, approximately 89.0% protein. The powder had a maximum of 5.4% moisture.

Trevor Berry at the University of Canterbury supplied a digital camera for use at Edendale's plants in July 2004. Fiona Russell and Inward Goods supplied the digital cameras at Clandeboye.

There were viewing ports in the lid of each calandria. These were useful for observing the liquid height in the distribution plate, general running conditions and understanding how the evaporators worked. A torch was shone into one port and another port was used for viewing. It was very difficult to photograph anything through these ports.

2.13 Sensitivity Analysis

A sensitivity analysis found the uncertainty in the values of the OHTCs, evaporation rates and wetting rates. The full analysis appears in Appendix A-9.

Equations for the wetting rate, evaporation rate, flash evaporation rate and OHTC were differentiated. This was to establish the sensitivity of the wetting rates and OHTCs to the uncertainty to the scatter in the measured process variables.

3. Results, Analyses and Discussions

This project covered a wide range of problems and tasks. There are separate sections for each of the different tasks. The following sections cover the problems and tasks encountered in this project.

3.1 The operating problems in the evaporators.

3.2 Single tube minimum wetting rates measured for various milks.

3.3 The current distributor designs.

3.4 Total solids measurements of milk in the evaporators.

3.5 Upward vapour flows in effect 2 of the evaporators.

The results are analysed and discussed in each section.

3.1 Evaporator Operating Problems

3.1.1 Problems

Tubes Blocking

There was a recurring tendency for some evaporator tubes to foul, sometimes to the extent of fully blocking. External water blasters were required to unblock the tubes. This fouling was unpredictable and operators frequently had to open Clandeboye's five Niro evaporators to check the condition of the tubes.

Table 3-15 shows there were 35 recorded tube blockages during the 2003-2004 season. There were 19 blocked tubes in effect 4.

Tube blocking was particularly common in effect 4. A design fault was the suspected cause. There were no recorded tube blockages in effect 1. It cost approximately NZ$1500 to unblock an evaporator tube and it cost approximately NZ$52,500 to unblock the 35 tubes during the season (Chris Johnson, personal communication, 2005). Of this, approximately NZ$28,500 was spent unblocking the effect 4 tubes.

Table 3-15: Records of blocked tubes in Clandeboye evaporators during the 2003-2004 season.

Effect – Pass	Evaporator					Total
	1	2	3	4	5	
2-1		1				1
2-2			1			1
2-3		3		1		4
2-4		1			1	2
2-5			4	1		5
3	3					3
4	13	6				19

Records and operator experience show that effect 4 of Evaporator 2 was the most likely pass to foul. Of recent note, a tube in effect 2 pass 5 of Evaporator 4 was blocked after sustained MPC-85 and MPC-70 production.

MVR Fans Reach Maximum Speed Early

Effect 2 had problems when processing some skim milks with medium-to-high protein contents. The speeds of the MVR fans rose throughout the run, until they reached 100%. At this point there was no control of the total solids concentrations out of effect 2 and the evaporator was shut down to be cleaned. Evaporators sometimes reached maximum fan speed after only 8 hours of continuous operation. Evaporators ran for up to 31 hours in the 2003-2004 season.

This problem was particularly common in Evaporators 1 and 2. It happened when processing skim milks. The MVR fan motors in Evaporators 3 to 5 were slightly larger than those in Evaporators 1 and 2 and their MVR configurations gave better operation. The problems in Evaporators 1 and 2 are reported to have happened every year at the beginning of the milk season (James Winchester, personal communication, 2004).

3.1.2 Results and Analysis

Viscous Fouling in Tubes

Figure 3-31 shows the fouling which formed at the bottom of a Niro evaporator before cleaning after a whole milk run. Figure 3-32 shows an extreme example of fouling that can occur in milk evaporators.

Figure 3-31: Fouling before cleaning at the end of a whole milk run.

Figure 3-32: Black fouling in blocked evaporator tubes.

Fouling deposits create sites for thermophilic bacteria growth which can contaminate the product and cause downgrades. Figure 3-32 shows how a series of inadequate cleans allows the fouling to darken and harden, forming a tough black material which is extremely difficult to remove.

Evaporator Scheduling

The five evaporators were shared between the CD1 and CD2 plants. Each dryer required two evaporators while processing skim or whole milks. One evaporator was always unused when CD1 and CD2 were both processing skim or whole milks. The evaporator was usually being cleaned or on standby. A precise swapping sequence occurred to ensure that one evaporator stopped every four hours. This was because it took four hours to fully clean an evaporator and only one evaporator could be cleaned at once. Typical evaporator swapping schedules for the CD1 and CD2 plants are shown in Figure 3-33.

The CD2 dryer required only one evaporator when it processed MPC-70 and MPC-85. When CD1 processed skim or whole milk, and CD2 processed MPC, there were two spare evaporators. One was being cleaned and the other was on standby. The availability of an extra evaporator made scheduling much easier.

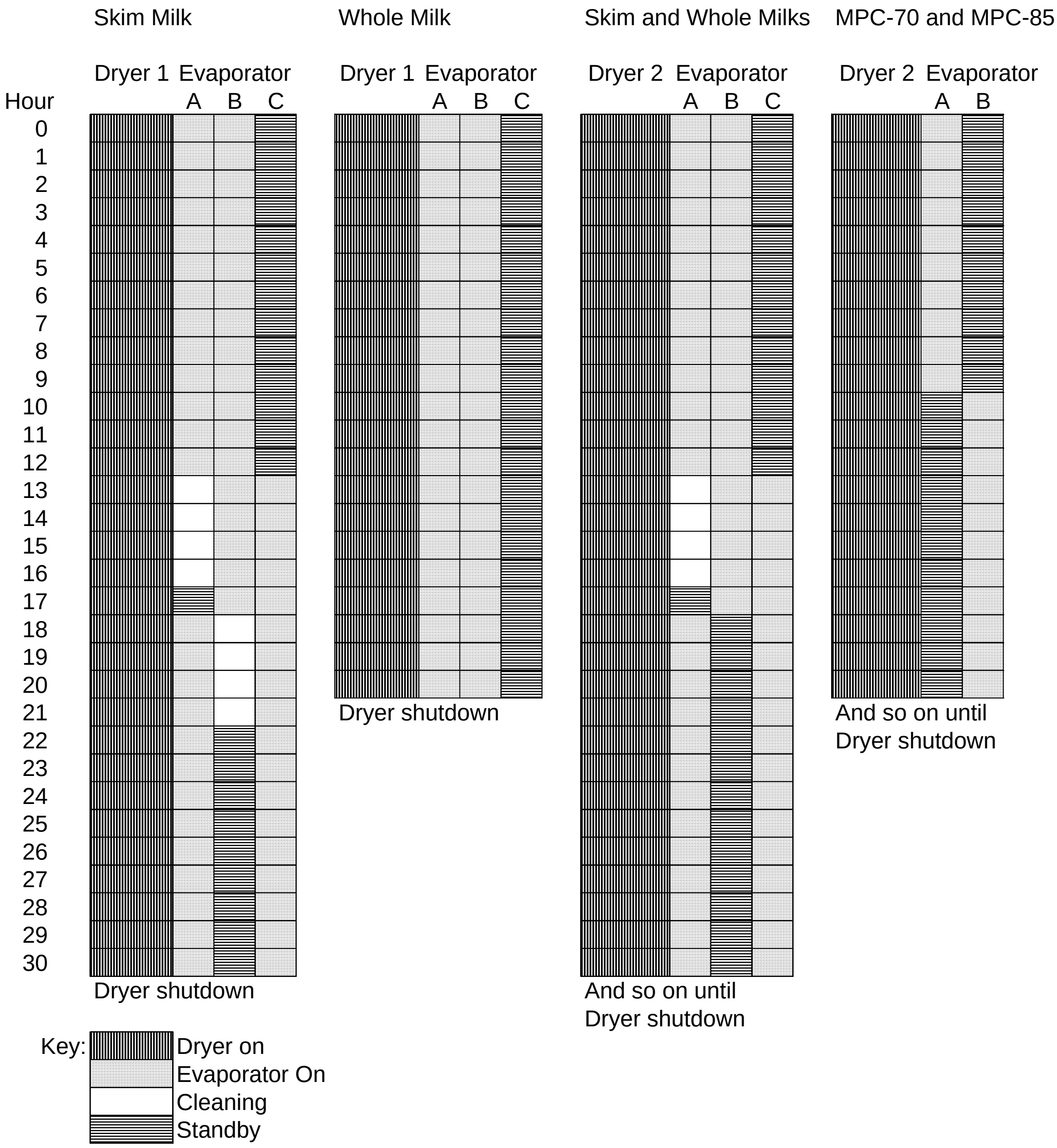


Figure 3-33: The evaporator swapping and cleaning sequence for the CD1 and CD2 dryers processing skim and whole milks, and MPCs in CD2.

The CD1 dryer can run for 24 or 30 hours, depending on milk type, milk supply and evaporator availability. It has a rotary atomiser which must be replaced periodically during a run. An atomiser and feedline swap took approximately one hour to compete. Whole milk runs were made as long as possible because there was only one dryer feedline with a homogeniser. The two evaporators started and stopped with the dryer. The whole milk run lengths were up to 25 hours long in the 2003-2004 milk season.

The CD1 dryer ran for typically 30 hours on skim milk. The first evaporator was taken off after 12 hours for cleaning, while the other one continued until it reached 18 hours. The replacement evaporators ran for 18 hours until the dryer was shut down. This sequence ensured that one evaporator shut down for cleaning every six hours.

The CD2 dryer had sets of nozzles which sprayed milk into the dryer. This makes it suitable for continuous operation.

MVR Fan Speeds

Figure 3-34 shows the MVR fan speed during a skim milk run in Evaporator 2. This run ended prematurely because the MVR fans reached maximum speed. The MVR fan speeds rose steadily while the feed flowrate was constant. This increased the temperature difference in effect 2.

The evaporator spent approximately 1 hour at maximum MVR speed. This caused a drop in the total solids of the milk exiting effect 2. The lack of control caused the evaporator to be shut down and cleaned.

This behaviour commonly occurred at the start of the milk season, and is thought to have been due to the composition of the milk at the time (James Winchester, 2004, personal communication). Shorter run lengths increased the number of cleans.

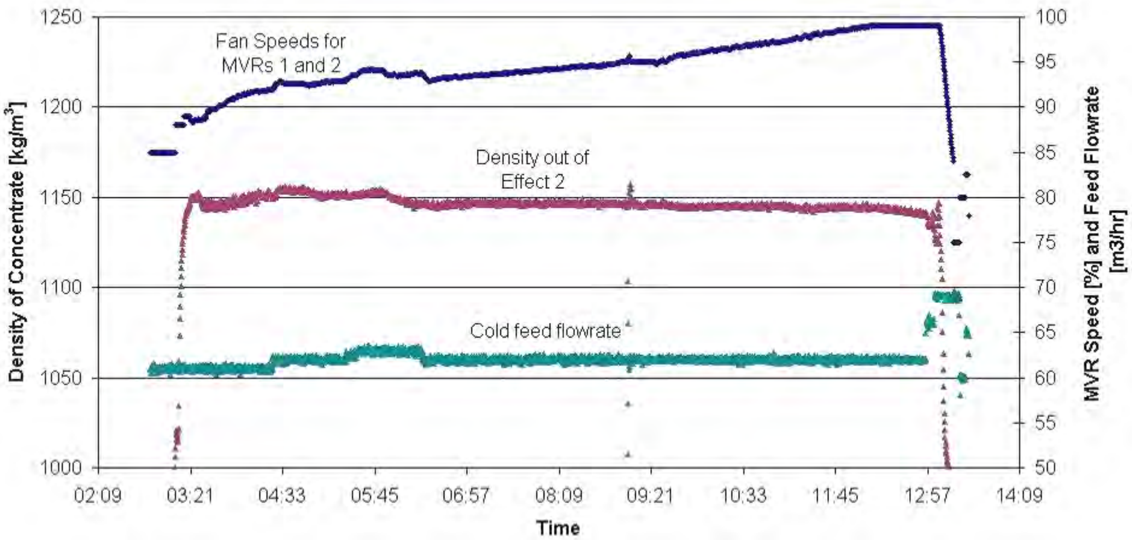


Figure 3-34: The fans speeds of MVR 1 and 2, the outlet milk density from effect 2 and the cold skim milk feed flowrate for Evaporator 2 while processing skim milk.

All Run Lengths

Figure 3-35 shows the frequency of run lengths for the season. This covers skim and whole milks, MPC-85 and MPC-70.

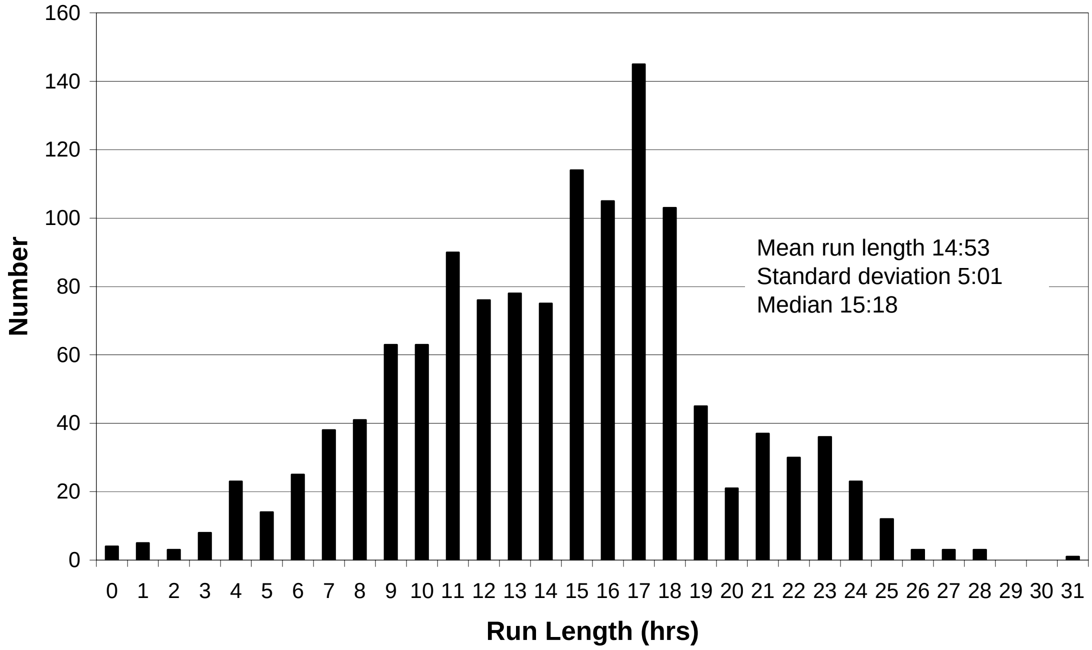


Figure 3-35: Numbers of run lengths in Evaporators 1 to 5 while processing skim milk, whole milk, MPC-70 and MPC-85 in the 2003-2004 milk powder season.

There was an extraordinary amount of variation in the run lengths. Most runs were expected to be between 18 and 20 hours. This clearly did not happen. The average run length was just under 15 hours. The maximum run length was 31 hours.

Reasons for evaporator shutdowns and cleaning are as follows:

- Low milk supply.
- Changes in the heat treatment or holding time for products.
- Re-cleaning because of an inadequate previous clean.
- Human error.
- Thermophile concerns.

From the middle of the 2003-2004 season, MPC-85 was run for a maximum of 10 hours because of thermophile concerns. Process problems and emergencies such as dryer ‘crashes’, pump breakdowns, problems with the static fluid bed and cyclone blocks in CD1 contributed to the high number of short runs.

Skim Milk Run Lengths

Figure 3-36 shows the number of runs with particular lengths for skim milk. There were 953 runs. These were processed in CD1 and CD2 throughout the milk powder season, especially during the periods of high milk supply from September 2003 to January 2004.

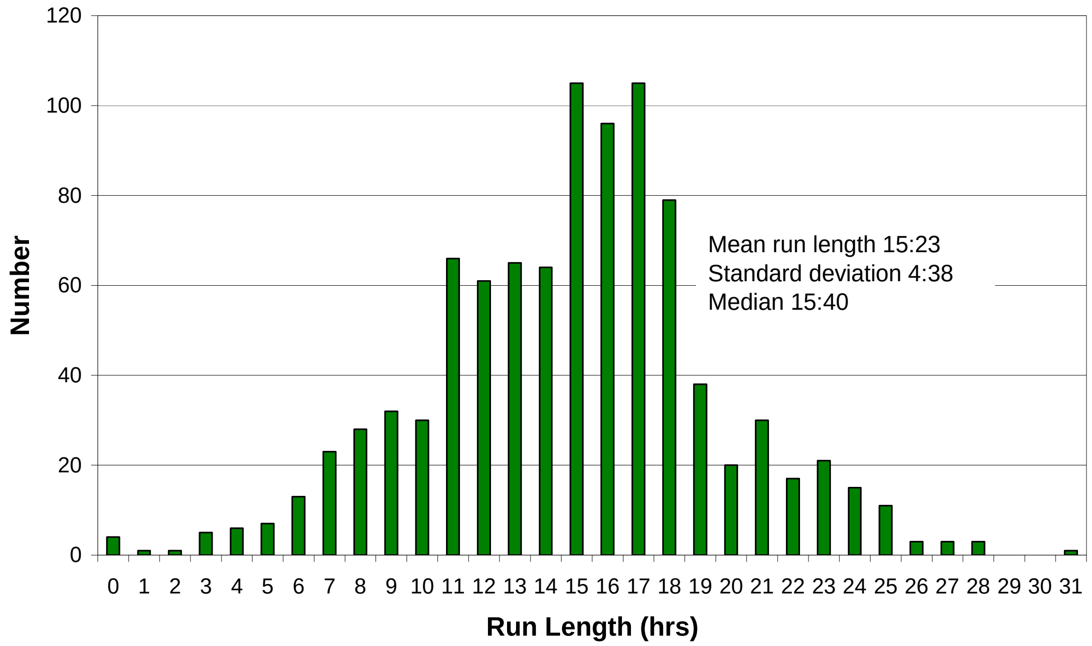


Figure 3-36: Numbers of run lengths in Evaporators 1 to 5 while processing skim milk in the 2003-2004 milk powder season.

The scheduling system for continuous operation meant that evaporators processing skim milk were meant to run for up to 18 hours. After the CD1 or CD2 dryer was started up, one of the two evaporators was taken off after 12 to 14 hours for cleaning. As a clean took between 3 and 4 hours, this allowed the cleaning equipment to be free when the other evaporator was taken off product at 18 hours. Subsequent evaporator runs were all 18 hours long until the dryer is shut down.

Most runs were expected to be between 17 and 18 hours long. Figure 3-36 shows this was not so. There were 375 runs which ran from 15 hours to just under 18 hours. 256 runs ran from 11 to just below 15 hours.

162 runs ran for 19 or more hours. These long runs occurred during the peak of the season when there was insufficient capacity to cope with milk supply. There was insufficient tie to clean evaporators so they were flushed with caustic soda to remove some of the protein fouling and continued in service until they could be fully cleaned.

There were 150 times when the evaporators ran for less than 11 hours. Emergency shutdowns, specification changes and short runs at the start of the season caused most of these short runs.

CD1 had a process disruption when the feed-line to the rotary atomiser was swapped. This required the dryer to be shut down for up to an hour. The evaporators were taken off product and rinsed. They were kept on standby and then returned to product. The frequency of feedline swaps in CD1 was 20 to 30 hours (James Winchester, personal communication, 2005). The feedline swaps in CD2 did not dryer shut down the dryer.

Logbooks from September to December 2003 show that there were 30 recorded instances when evaporators were shut down prematurely due to the MVR fans reaching maximum speed. Another evaporator had to be used to cover for the dirty one, disrupting process plans. It is difficult to state the number of 'extra' cleans caused by an early shutdown, as the production plans changed to accommodate new situations.

These runs were explicitly recorded by the operator as being shut down because of the MVR fans. A more thorough analysis of the logbooks is likely to show other runs which were shut down early but were not recorded, or were operated more conservatively to avoid the fans reaching maximum speed.

Skim milk specification 6420 created most of the early shutdowns during the 2003-2004 season. This specification was unstandardised skim milk and was known by staff as an easily-fouling milk. It was unstandardised because of the milk oversupply during the October-November peak of the season. This specification was used for minimum wetting measurements by Tandon (2004), Riley (2004) and measurements for this thesis.

It is unlikely that unstandardised milk will be processed at Clandeboye in the future. MPC production in CD2 has increased considerably since the ultra-filtration plant upgrade in the 2004 off-season.

Whole Milk Run Lengths

Figure 3-37 shows the number of runs of particular lengths for whole milk. It was processed mostly in CD1 in August and from March to May 2004.

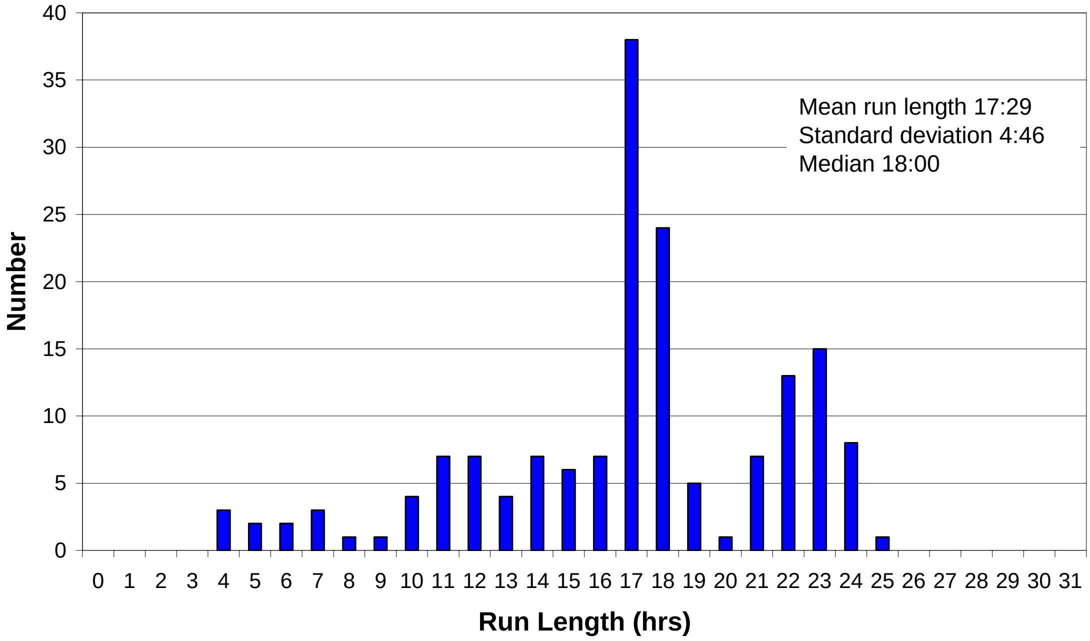


Figure 3-37: Numbers of run lengths in Evaporators 1 to 5 while processing whole milk in the 2003-2004 milk powder season.

There was a peak of 62 runs between 17 and less than 19 hours. These were the expected run lengths for when there was continuous operation in CD1 and CD2.

There were 50 runs over 19 hours. At times of low milk supply, the dryer and evaporators were run together for as long as possible. Thermophile constraints now limit the evaporators to a maximum of 20 hours.

There were 54 runs between 4 and 16 hours long. Some of these will be the 12 hour shutdown at the start of continuous operation. Others were short runs at times of low milk supply.

MPC Run Lengths

Figure 3-38 shows to the run lengths of both MPC-85 and MPC-70. There were 161 runs.

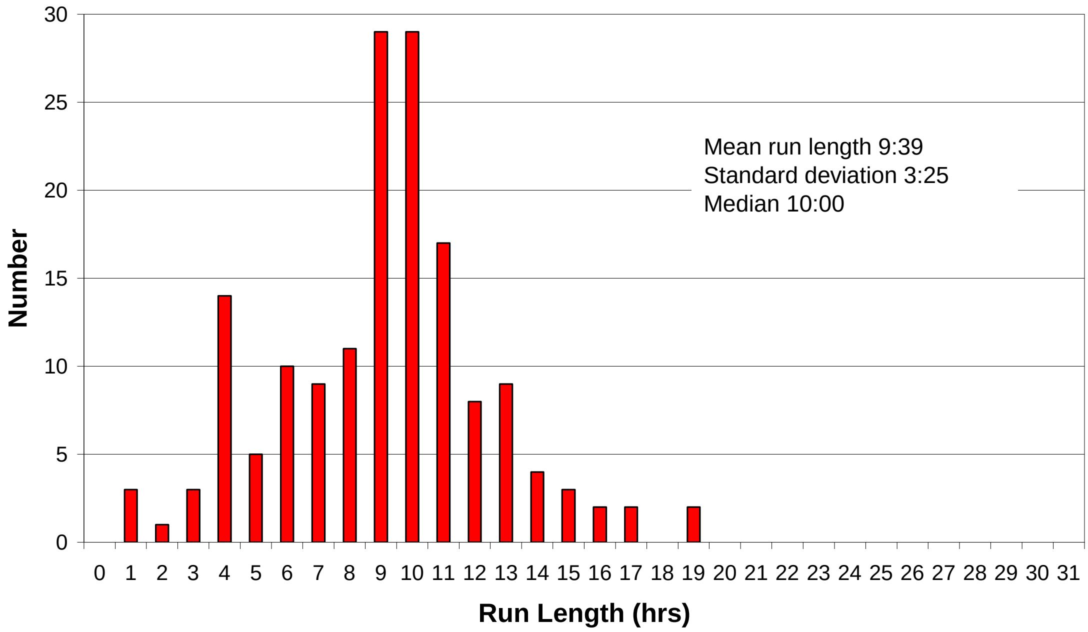


Figure 3-38: Frequency of run lengths in Evaporators 3 to 5 processing MPC-70 and MPC-85 in the 2003-2004 milk powder season.

The run lengths were initially up to approximately 18 hours. The average run length was nearly 10 hours. There was a peak of 58 runs between 9 and less than 11 hours. They were limited to 10 hours halfway through the season due to thermophile and other concerns. There were 47 runs above 11 hours.

There were 56 very short runs below 9 hours. During the 2003-2004 season there was insufficient capacity in the ultra-filtration plant to process MPCs for continuous production in the milk powder evaporators. This gave the short runs. MPCs foul the evaporator surfaces easily and the evaporators had to be cleaned after each short run. An ultra-filtration plant upgrade can now supply continuous volumes of MPCs to the evaporators.

3.1.4 Conclusions

There were problems with liquid distribution in Fonterra Clandeboye's Evaporators 1 to 5. There were 35 blocked tubes in the evaporators during the 2003-2004 milk season which required water blasting to clear. Occasionally the MVR fans would reach maximum speed while the evaporators processed skim milk, forcing the evaporator to shut down and be cleaned.

The run lengths showed that thermophile concerns rather than fouling limited the maximum run lengths of the evaporators. Process scheduling and emergencies contributed to the many short evaporator runs.

Most of the season's milk processing was for skim milk. The average run length was just under 15 hours. The average run length was expected to be approximately 18 hours.

Whole milk had an average run length of 17.5 hours. There were fewer whole milk runs than skim milk.

MPCs had an average run length of 9.4 hours. There maximum run length was set in the middle of the season at 10 hours because of thermophile and fouling concerns.

This shows that the growth of thermophilic bacteria in the evaporators, encouraged by fouling, had a significant impact on the run lengths of the evaporators.

3.2 Single Tube Minimum Wetting Rates

3.2.1 Introduction

The Department of Chemical and Process Engineering at the University of Canterbury had a 'Wetting Rig' which was used to determine the minimum wetting rate of milk on the inside of a stainless steel evaporator tube. Reconstituted spray dried whole milk, standardised skim milk and MPC-85 were tested. MPC-85 is milk protein concentrate with 85% protein on a dry mass basis. The milks were tested at 60ºC under heat transfer and evaporation conditions with a 5ºC temperature difference, and under isothermal conditions at 60ºC. These conditions replicated evaporator operating conditions.

This section discusses the general observations made while performing the trials and separate sections cover the minimum wetting rates for each milk type under isothermal, heat transfer and evaporation conditions.

3.2.2 General Observations

Shapes of Dry Patch Curvature

The shapes of curvature at the top of the dry patches were rather 'flat' for skim milk and MPC-85 (Figure 3-39).

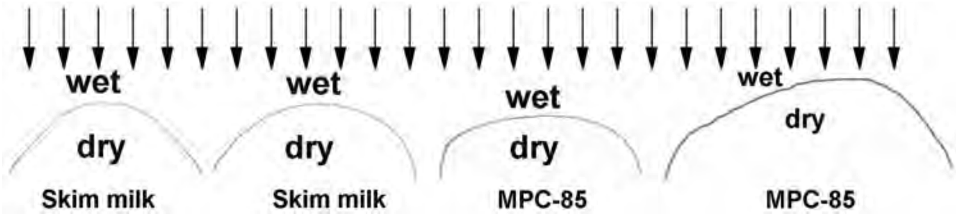


Figure 3-39: The typical dry patch shapes at the top of the tubes for skim milk and MPC-85 immediately before complete wetting.

The shape of an MPC-85 dry patch was more horizontal or 'flatter' than for skim milk. The liquid film advanced onto dry patches more rapidly for MPC-85 than skim milk. Concentrated MPC-85 was much more viscous than skim milk. The differences between the two milks were more obvious for milk concentrates than dilute solutions.

Whole milk behaved quite differently. The shapes of typical dry patches were much 'steeper.' Figure 3-40 shows some unexpected dry patch shapes for whole milk.

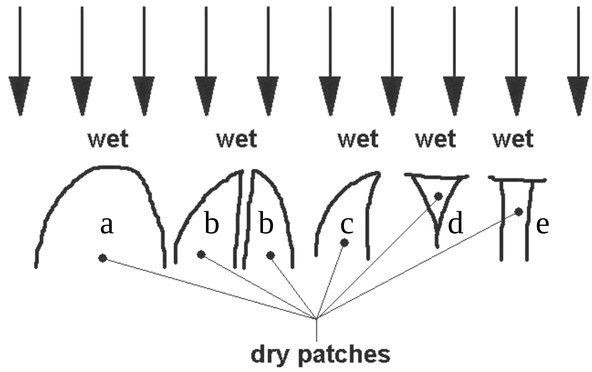


Figure 3-40: Different dry patch shapes for whole milk.

The five dry patches in Figure 3-40 are discussed from left to right. The first dry patch (a) is typical for whole milk. It has a much 'steeper' shape than skim milk or MPC-85. As the wetting rate increased, the liquid film would either slowly cover the dry patch or a trickle would sometimes break at the centre, leaving two smaller dry patches on either side (b). An increase in the wetting rate would cause one of these dry patches to eventually break, leaving a solitary dry patch with the shape of (c). There were also some other oddly-shaped dry patches such as the shape in (d), and a vertical dry patch in (e). These both had unusual shapes at the top. The presence of such oddly-shaped dry patches caused whole milk to have higher minimum wetting rates than skim milk or MPC-85.

Bubbles under evaporation conditions

The minimum wetting rates for evaporation conditions were higher than under heat transfer conditions. The temperature differences were 5ºC. During evaporation conditions, bubbles slowly formed on the tube surface, creating dry 'holes' on the liquid film. The bubbles occurred down the length of the tube. This suggested nucleate boiling was occurring rather than convective film evaporation. Incropera & DeWitt (2001) give a Nukiyama curve for water at atmospheric pressure (Appendix A-14) where 5ºC is expected to be the transition point between convective film and nucleate boiling. A higher milk flowrate was required to wet these dry patches and if left a long time protein fouling formed on the edges of the 'holes.'

During evaporation conditions, concentrated MPC-85 fouled easily. Rodriguez Patino *et al*. (1995) mention that proteins move to the liquid-gas interface when foam forms. Protein appeared to move to the edge of the bubbles and dry out. This fouling made it more difficult to wet the surface, increasing the minimum wetting rate.

The viscosity of MPC-85 increased dramatically above 24%. The liquid was so viscous at 25% that the pump was only able to achieve a wetting rate of about 0.10 kg $m^{-1}s^{-1}$ when the liquid was at 60ºC. A small change in total solids for concentrated MPC-85 caused a large increase in viscosity. A study is recommended for the viscosity of MPC-85.

Concentrated MPC-85 tended to dry in the presence of air when it was left stagnant. An open beaker of MPC-85 at 50ºC formed a sticky protein layer after only 10 minutes. Protein layers built up in areas of low flow in the wetting rig, such as the point where the distributor sat on the tubesheet and sometimes inside the holes of the nylon distributor ring. It was difficult for cleaning chemicals to dissolve this protein.

3.2.3 Minimum Wetting Rates

The following subsections describe and discuss the minimum wetting rates under isothermal, heat transfer and evaporation conditions. The minimum wetting rates of skim and whole milks and MPC-85 are provided in each sub-section. Figure 3-41 provides a summary of all the results and the uncertainties.

Uncertainties were evaluated as half the difference between the maximum and minimum values for a data set. At least two measurements were made for each condition.

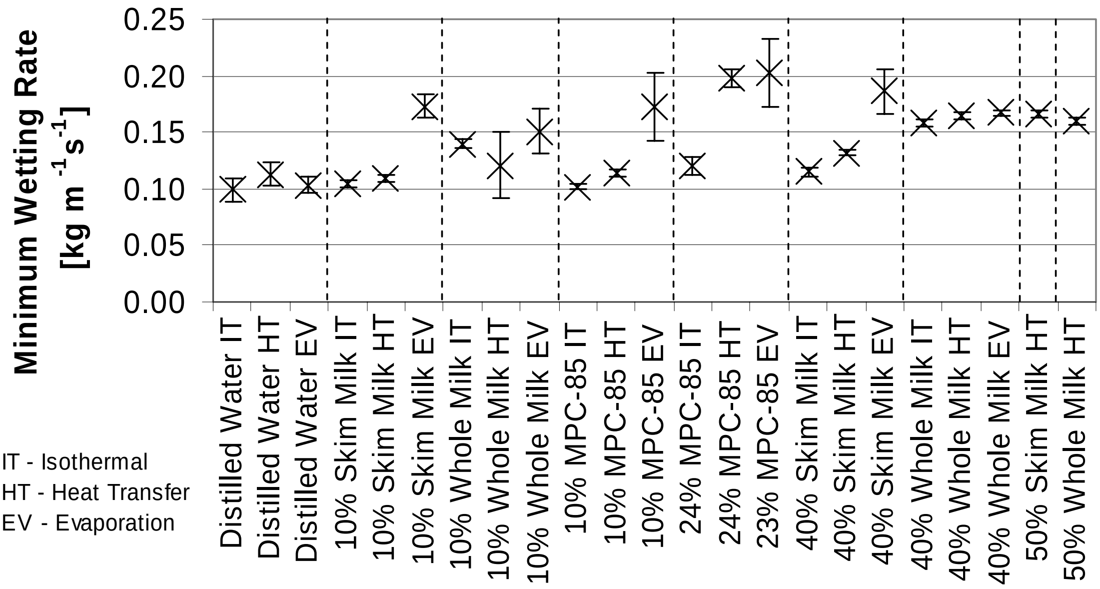


Figure 3-41: Summary of the single tube minimum wetting rates and uncertainties for reconstituted whole milk, standardised skim milk and MPC-85 at various concentrations under isothermal, heat transfer and evaporation conditions.

Isothermal Wetting Rates

Figure 3-42 shows the minimum wetting rate for distilled water, skim and whole milks, and MPC-85 under isothermal conditions at 60ºC. The figure shows measurements from Tandon (2004) and values predicted by Tandon (2004) using the equation from Hartley and Murgatroyd (1964). More information on the minimum wetting rate measurements appear in Appendix A-2.

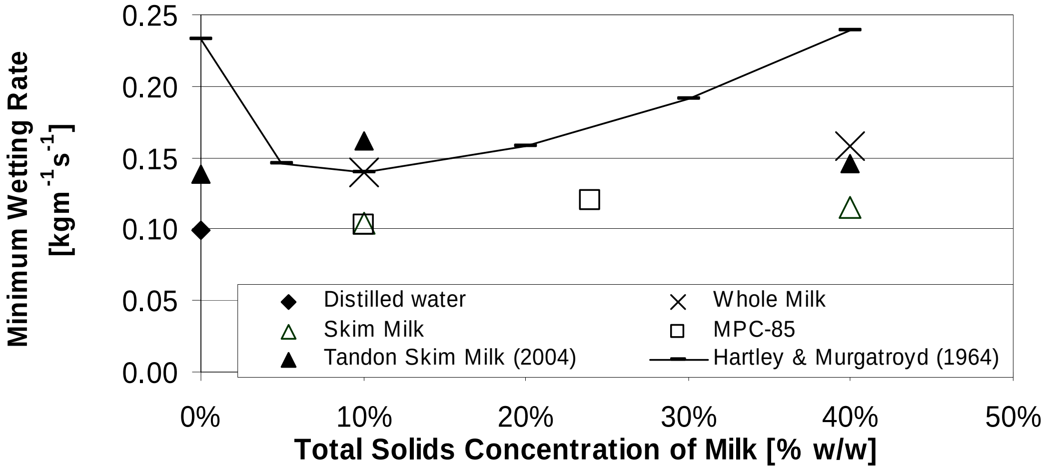


Figure 3-42: Minimum wetting rates for standardised skim milk, whole milk and MPC-85 in a dry evaporator tube versus total solids under isothermal conditions at 60ºC.

Distilled water had the lowest minimum wetting rate. It was 0.099 kg $m^{-1}s^{-1}$ with an uncertainty of ± 0.012 kg $m^{-1}s^{-1}$. This is much lower than the values predicted by Hartley and Murgatroyd (1964) of 0.186 kg $m^{-1}s^{-1}$. The use of a more effective distributor gave lower values than the value of 0.139 kg $m^{-1}s^{-1}$ from Tandon (2004).

For the 10% milks, whole milk had a significantly higher minimum wetting rate than skim milk or MPC-85. The minimum wetting rate for whole milk was 0.140 kg $m^{-1}s^{-1}$, for skim milk it was 0.104 kg $m^{-1}s^{-1}$ and for MPC-85 the value was 0.102 kg $m^{-1}s^{-1}$.

For milk concentrates, the minimum wetting rate of 40% whole milk was higher than for 40% skim milk and 24% MPC-85. The minimum wetting rate of 40% whole milk was 0.158 kg $m^{-1}s^{-1}$, the value for 40% skim milk was 0.115 kg $m^{-1}s^{-1}$ and the value for 24% MPC-85 was 0.120 kg $m^{-1}s^{-1}$. These values were slightly higher than for the 10% milks.

The tendency for whole milk to form small dry patches down the length of the tube increased its minimum wetting rate. Skim milk and MPC-85 did not form similar dry patches down the length of the tube, and had lower minimum wetting rates.

The predictions from Hartley and Murgatroyd's force balance correlations appear to give overestimations for the minimum wetting rates of distilled water and milks. The improved distributor design allowed the minimum wetting rates for 10% and 40% skim milks to be lower than the values from Tandon (2004).

Minimum Wetting Rates with Heat Transfer

Figure 3-43 shows the minimum wetting rate for skim and whole milks, and MPC-85 at 60ºC under heat transfer conditions with a 5ºC overall temperature difference. The heat flux was estimated as approximately 1650 W $m^{-2}K^{-1}$ (Robinson, 2004, p. 29).

Distilled water had a minimum wetting rate of 0.113 kg $m^{-1}s^{-1}$ with an uncertainty of 0.013 kg $m^{-1}s^{-1}$. This was similar to the value obtained by Tandon (2004) which was 0.142 kg $m^{-1}s^{-1}$ and the value by Riley (2004) which was 0.133 kg $m^{-1}s^{-1}$.

For 10% milks, the minimum wetting rate of whole milk was similar to skim milk and MPC-85. The minimum wetting rate of whole milk was 0.121 kg $m^{-1}s^{-1}$, the value for skim milk was 0.109 kg $m^{-1}s^{-1}$ and the value for MPC-85 was 0.114 kg $m^{-1}s^{-1}$. Whole milk was much more susceptible to random variation with a large uncertainty of ± 0.03 kg $m^{-1}s^{-1}$ compared to the uncertainty of ± 0.003 kg $m^{-1}s^{-1}$ for skim milk and MPC-85. Faint ripples were observed as all three milks flowed down the tube.

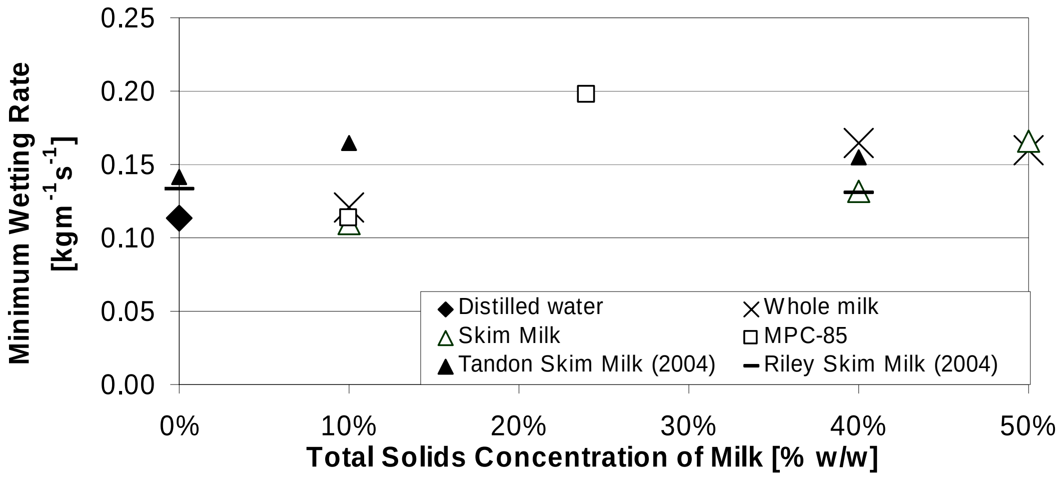


Figure 3-43: Minimum wetting rates for whole milk, standardised skim milk and MPC-85 in a dry evaporator tube versus total solids concentration under heat transfer conditions with a 5ºC temperature difference at atmospheric pressure.

The minimum wetting rate of 40% whole milk was 0.164 kg $m^{-1}s^{-1}$. This was higher than the minimum wetting rate of 40% skim milk which was 0.132 kg $m^{-1}s^{-1}$. The uncertainties were smaller with values of ± 0.003 kg $m^{-1}s^{-1}$ for both milks. The minimum wetting rates for 40% whole milk and 40% skim milk were distinctly higher than for the 10% milks. There were distinct ripples as the milks flowed down the tube.

The 24% MPC-85 had very strong ripples and much higher minimum wetting rates than when under isothermal conditions. The heat transfer minimum wetting rate was 0.198 kg $m^{-1}s^{-1}$ while the rate under isothermal conditions was 0.120 kg $m^{-1}s^{-1}$. The uncertainty was ± 0.008 kg $m^{-1}s^{-1}$. Replications using the same liquid sample confirmed that the minimum wetting rate increased dramatically when there was a 5ºC temperature difference.

There was no significant difference in the minimum wetting rates as the concentration of whole milk was raised from 40% to 50% TS. The minimum wetting rate of 40% whole milk was 0.164 kg $m^{-1}s^{-1}$, and at 50% the value was 0.160 kg $m^{-1}s^{-1}$. The uncertainties were ± 0.003 kg $m^{-1}s^{-1}$.

There was an increase in the minimum wetting rates as the total solids of the skim milk concentrate increased. The minimum wetting rate was 0.132 kg $m^{-1}s^{-1}$ for 40% skim milk while at 50% the minimum wetting rate was 0.166 kg $m^{-1}s^{-1}$. The uncertainties were ± 0.003 kg $m^{-1}s^{-1}$.

Evaporation Minimum Wetting Rates

Figure 3-44 shows the minimum wetting rate under evaporation conditions at 60ºC with a 5ºC temperature difference.

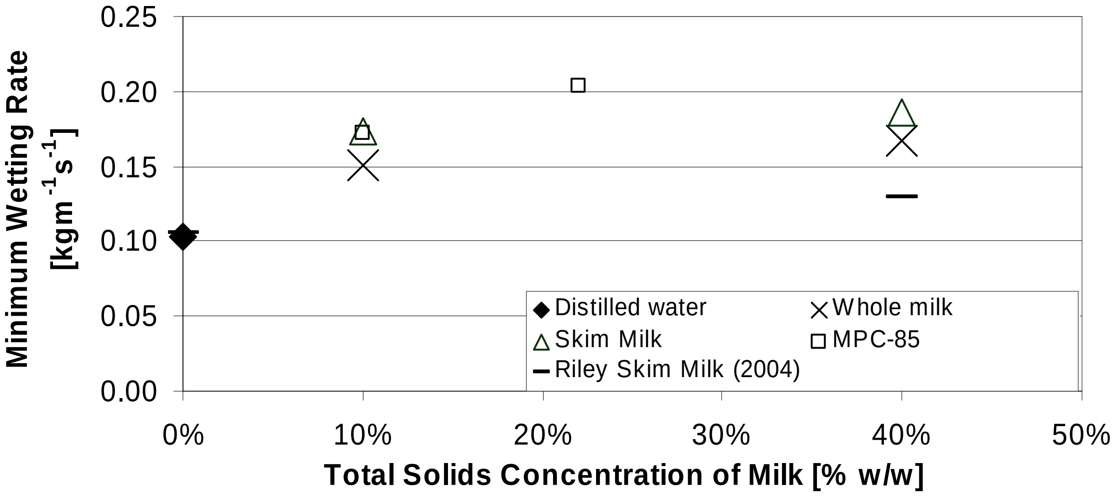


Figure 3-44: Minimum wetting rates for whole milk, standardised skim milk and MPC-85 in a dry evaporator tube versus total solids concentration under evaporation conditions at 60ºC with a 5ºC temperature difference.

The minimum wetting rate for distilled water was 0.103 kg $m^{-1}s^{-1}$. This was similar to the minimum wetting rates under isothermal and heat transfer conditions. The uncertainty was ± 0.003 kg $m^{-1}s^{-1}$. The wetting rate value was similar to the 0.105 kg $m^{-1}s^{-1}$ obtained by Riley (2004).

The minimum wetting rates of skim milk, whole milk and MPC-85 under vacuum evaporation conditions were considerably higher than for isothermal or heat transfer conditions.

The minimum wetting rate for 10% whole milk was 0.151 kg $m^{-1}s^{-1}$ and had a large uncertainty of ± 0.020 kg $m^{-1}s^{-1}$. The value for 10% whole milk was 0.121 kg $m^{-1}s^{-1}$ under heat transfer conditions.

The minimum wetting rate of skim milk was 0.173 kg $m^{-1}s^{-1}$ and had an uncertainty of ± 0.003 kg $m^{-1}s^{-1}$. The value for 10% skim milk was 0.109 kg $m^{-1}s^{-1}$ under heat transfer conditions.

The minimum wetting rate for MPC-85 was 0.172 kg $m^{-1}s^{-1}$ and had an uncertainty of ± 0.003 kg $m^{-1}s^{-1}$. The value for 10% MPC-85 was 0.114 kg $m^{-1}s^{-1}$ under heat transfer conditions.

The minimum wetting rate for 40% whole milk was higher than 10% whole milk. The minimum wetting rate for 40% whole milk was 0.167 kg $m^{-1}s^{-1}$, while the value for 10% whole milk was 0.151 kg $m^{-1}s^{-1}$.

There was little difference between the minimum wetting rate of 10% and 40% skim milks under evaporation conditions. The minimum wetting rate of 40% skim milk was 0.186 kg $m^{-1}s^{-1}$ and for 10% skim milk the value was 0.173 kg $m^{-1}s^{-1}$. There was a large uncertainty of ± 0.01 kg $m^{-1}s^{-1}$ for 10% skim milk, and ± 0.02 kg $m^{-1}s^{-1}$ for 40% skim milk.

The pump could not achieve a wetting rate above 0.10 kg $m^{-1}s^{-1}$ for 25% MPC-85 at 60ºC due to its high viscosity. For 22% MPC-85, the tube was fully wet at the top but a dry patch halfway down the tube was nearing breaking at a wetting rate of 0.203 kg $m^{-1}s^{-1}$. At this point the pump reached maximum speed. Although the tube was not fully wet, this value was shown to illustrate the higher minimum wetting rate of MPC-85 above approximately 22%. As a comparison, the minimum wetting rate for 24% MPC-85 under heat transfer conditions was quite similar, at 0.198 kg $m^{-1}s^{-1}$ with a large uncertainty of 0.08 kg $m^{-1}s^{-1}$.

Effect 4 typically handled 25% MPC-85 at 48ºC to 50ºC. The MPC-85 out of effect 3 was typically 24% at approximately 53ºC. It was not possible to test MPC-85 in the wetting rig at these concentrations because of the high viscosities.

Discussion of Boiling Regimes

Bubbles slowly formed in the surface of the wall for three milks under evaporation conditions when the temperature difference was 5ºC. The bubble sizes were approximately 2 to 5 mm across. Incropera & DeWitt (2001) show that for water evaporating at atmospheric pressure with a temperature difference of 1ºC to 5ºC there is free convection and that between 5ºC and 10ºC there are isolated bubbles forming through nucleate boiling. Notable papers investigating the transition between convective film and nucleate boiling for milk include Müller-Steinhagen (1989), Billet (1989, p. 139) and Houšová (1970). The wetting rig should be used to investigate the behaviour of dilute and concentrated forms of skim milk, whole milk and MPC-85 under different temperature differences while evaporating under a vacuum.

Effects 1 and 2 were typically run with temperature differences of 3ºC. The TVR effects ran with temperature differences higher than 4ºC. Effect 3 runs between 4ºC and 7ºC, while effect 4 ran between 4ºC and 11ºC, depending on fouling. This means the heat transfer minimum wetting rates are likely to be more appropriate for effects 1 and 2, where negligible bubble formation is expected. Nucleate boiling was suspected in effects 3 and 4 and it is likely that the evaporation minimum wetting rates were more appropriate.

3.2.4 Conclusions

The dry patches of reconstituted skim milk and MPC-85 on stainless steel evaporator tubes had similar broad shapes. Whole milk had a much 'steeper' dry patch shape. This contributed to whole milk having a higher minimum wetting rate than the other milks.

The minimum wetting rates of skim milk, whole milk and MPC-85 were between 0.10 and 0.20 kg $m^{-1}s^{-1}$ and were higher than the minimum wetting rates for distilled water. The minimum wetting rate rose as the total solids concentration of the milks increased.

The minimum wetting rates under heat transfer conditions were lower than for evaporation conditions. This is because bubbles formed on the surface of the tube under evaporation conditions and prevented the tubes from fully wetting. Research should be done regarding the influence of the temperature difference on the evaporation of milk under a vacuum.

3.3 Current Distributor Design

3.3.1 Overview

The design of the distribution system was thoroughly investigated. This involved the following tasks:

- Taking the dimensions of the distribution plates.
- Counting tube and hole numbers.
- Measuring hole sizes.
- Checking whether the liquid distribution sections are all fabricated properly and consistent with each other.
- Analysing the flows of liquid from the holes to the tubes.
- Testing the effectiveness of liquid distribution in the evaporators.
- Observing the evaporators before cleaning to find any fouling.
- Working with staff to find any concerns related to liquid distribution.

The following subsections report and discuss these tasks.

3.3.2 Liquid Distribution Designs

The following figures show the designs of the distribution plates. Figure 3-45 shows the general design of effect 1 and Figure 3-46 displays the design of effect 2. Figure 3-47 shows a photo of the underside of effect 3 and Figure 3-48 shows the underside of effect 4. Figure 3-49 and Figure 3-50 show the top of the tubesheets in effects 3 and 4.

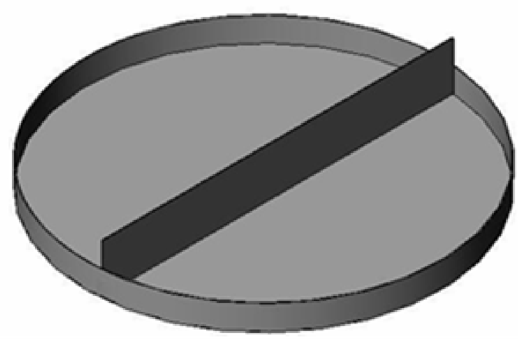


Figure 3-45: The effect 1 distribution plate.

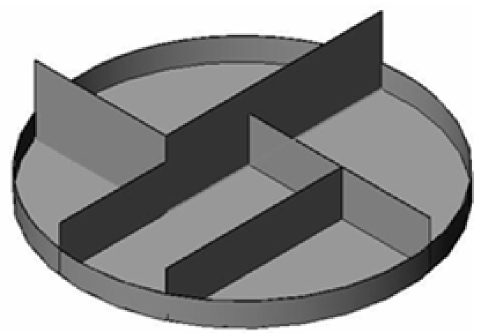


Figure 3-46: The effect 2 distribution plate.

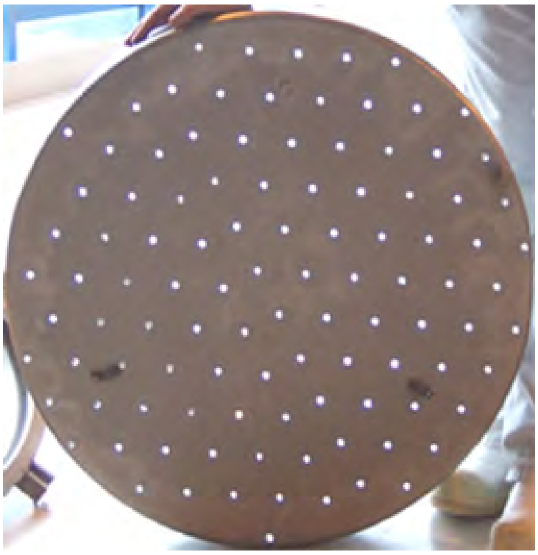


Figure 3-47: The effect 3 distribution plate, viewed from the bottom.

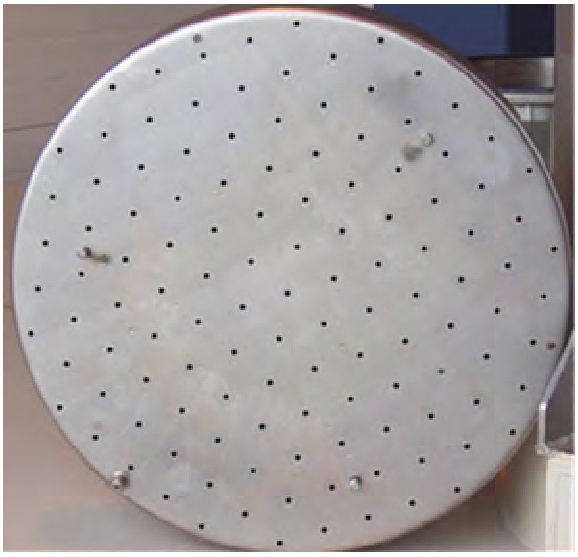


Figure 3-48: The effect 4 distribution plate, viewed from the bottom.

The distribution plates for effects 1 and 2 were very large and heavy. They were 2.2 m in diameter. They lay 40 mm above the tubesheet and rested on partitions.

The distribution plates for effects 3 and 4 had diameters of 0.7 m. They were lighter and could be removed by hand from the effects. The plates lay 25 mm above the tubesheet and rested on three supports.

Figure 3-49: The effect 3 tubesheet.

Figure 3-50: The effect 4 tubesheet.

Effects 3 and 4 operated as single-pass units. However, Figure 3-49 and Figure 3-50 clearly show that they were designed as two pass units. Niro's website details how milk concentrate calandrias can be divided into two passes to improve wetting (Niro, 2004).

Fonterra staff suspected that Niro designed effects 3 and 4 with a split in the middle so that the milk concentrate would not fall onto the cleaning set and build up (Richard Hickson, personal communication, 2005). The cleaning set was a circular ring with holes and its supply line. The cleaning sets at Clandeboye or Edendale were directly underneath the tubes. Fouling is reported to have formed on these cleaning sets. Unfortunately, none was observed during this project. Figure 3-70 (p. 86) shows that fouling formed on the tubesplit rather than on the cleaning set when MPCs were processed.

3.3.3 Hole Sizes

Figure 3-51 shows that the hole diameters in the CD1 and CD2 evaporators. Figure 3-52 shows the hole diameters for the ED2 and ED3 evaporators. The ED3 sizes were treated as the 'correct' hole sizes.

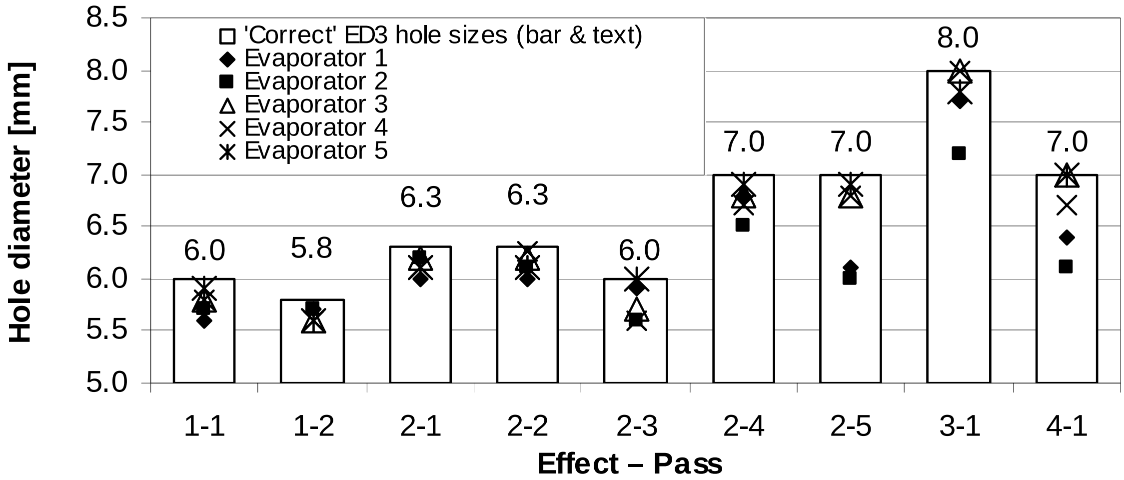


Figure 3-51: Hole diameters in Evaporators 1 to 5 at Fonterra Clandeboye.

There were some inconsistencies in the hole sizes for Clandeboye's evaporators, particularly in CD1. There were undersized holes in Evaporators 1 and 2. These were in pass 5 of effect 2. The holes were significantly smaller than expected in effect 4 of Evaporators 1, 2 and 4. It was very surprising that the holes sizes in effect 4 of Evaporator 1 were different to those in Evaporator 2, as they were built together.

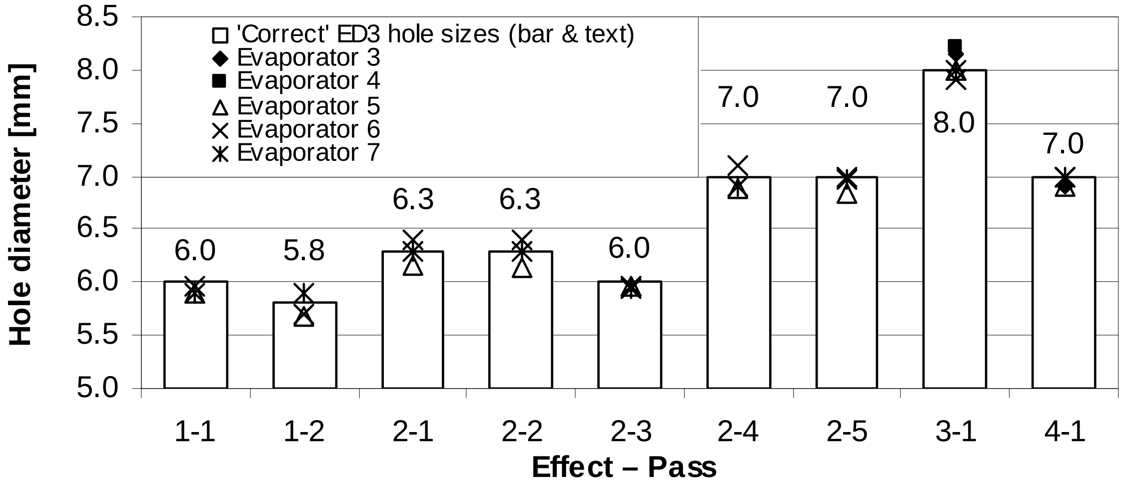


Figure 3-52: Hole diameters in Evaporators 3 to 7 at Fonterra Edendale.

The smaller hole sizes in effect 4 mean that the total hole areas are considerably smaller in Evaporators 1 and 2 than the other evaporators. Figure 3-53 shows the ratio of the total hole area in effect 4 of Evaporators 1 and 2 compared to the total hole areas in

Evaporators 3 and 5. These have ‘correct’ hole sizes of 7.0 mm. The ratio is expressed as a percentage.

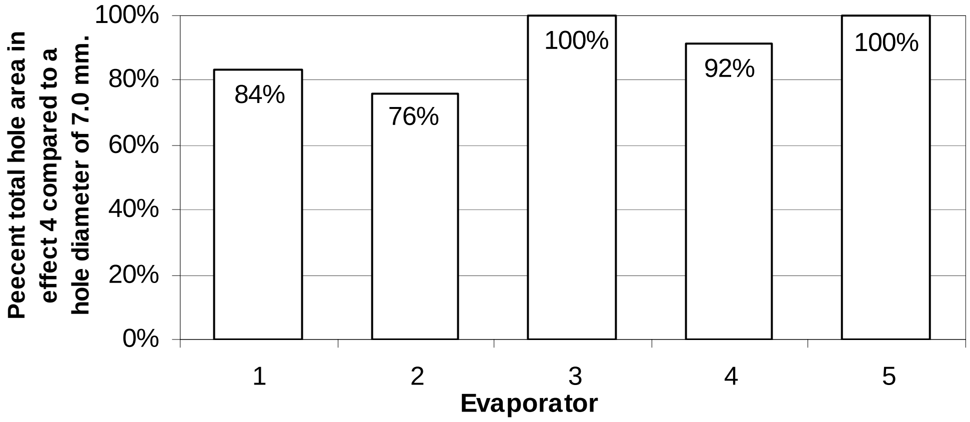


Figure 3-53: Ratio of total hole area in effect 4 of Clandeboye’s Evaporators 1 to 5, compared to a distribution plate with a hole size of 7.0 mm.

The smaller hole sizes in effect 4 of Evaporators 1, 2 and 4 mean that a greater liquid head height is required for a given flow into the tubes. The effect 4 distribution plates have been observed many times overflowing while processing skim and whole milks.

3.3.4 Tube and Hole Numbers

Table 3-16 shows the number of holes and tubes in each pass of the evaporators. As the tubesheets in effects 3 and 4 have a two-pass appearance, the ratios are also shown for these ‘passes.’ The larger ‘pass’ in each effect is denoted as ‘A’, while the smaller one is ‘B.’

The number of tubes along each successive pass of an evaporator should reduce to maintain suitable wetting rates as the milk flowrates decrease. Surprisingly, effect 4 has more tubes than effect 3. There are 96 tubes in effect 4, while effect 3 has only 80. Niro has not provided a suitable explanation why this is so.

There was a ‘rule of thumb’ in the industry that there were as many holes as there were tubes (James Winchester, personal communication, 2004). Table 3-16 shows there are always more holes than tubes.

Table 3-16: The number of distribution plate holes and number of tubes in all the evaporator passes and in the apparent passes in effects 3 and 4.

Effect–Pass	Number Of Holes	Number of Tubes
1–1	658	615
1–2	524	485
2–1	355	322
2–2	271	242
2–3	249	219
2–4	174	150
2–5	134	114
3	102	80
4	121	96
3–A	59	47
3–B	43	33
4–A	66	53
4–B	55	43

3.3.5 Relative Flows into Tubes

The flows of liquid from holes to tubes were analysed for each pass. This revealed that there were misdistributions in every pass, particularly in effects 3 and 4. Tubes on the edge of a pass received more liquid than the inner tubes. This is because the holes on the edge fed only one or two tubes, while they were sized to feed three.

A dimensionless fraction was used to show the extent of misdistribution in the tubes. This was called a relative flow. It was the ratio of the flow into a tube divided by the flow through a hole. A tube was supposed to receive the same flowrate as that from a hole. For example, a tube that receives a relative flow of 1.3 received 1.3 times the liquid flowing through a hole. Tubes which were not on the edge of the tubesheet received a relative flow of 1.0. The following subsections show and discuss the theoretical misdistributions in pass 5 of effect 2, effect 3 and effect 4.

Misdistribution in Pass 5 of Effect 2

Figure 3-54 shows the relative flows which are expected in effect 2 pass 5. This shows how the geometry of the tubes influences the flows entering tubes. The tubes on the outside of the pass all received larger flowrates than the inner tubes.

This pass had the highest ratio of edge tubes to inner tubes out of all the passes in effects 1 and 2. This means it had the largest misdistribution of these passes. Figure 3-55 shows the relative flow into each tube, cumulatively for all tubes.

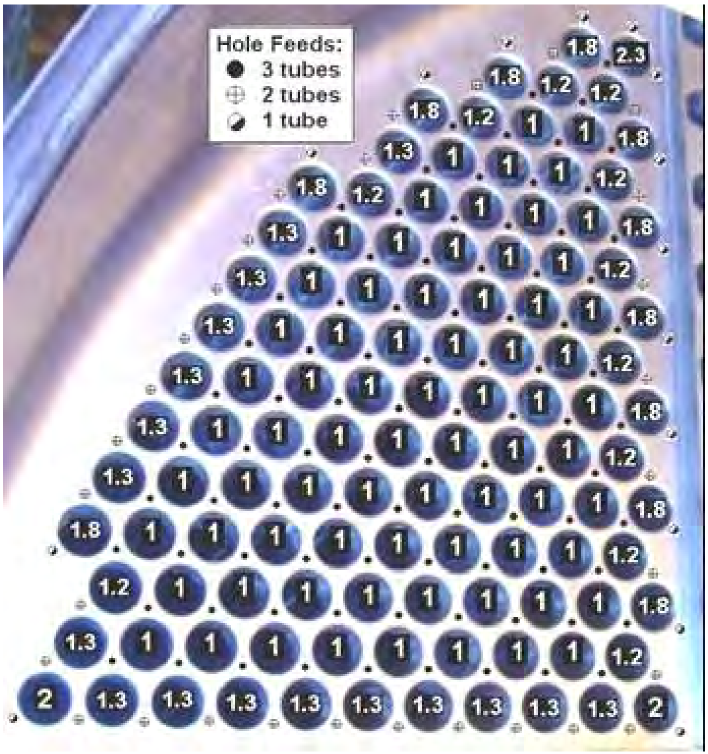


Figure 3-54: Relative flows into the tubes for effect 2-5.

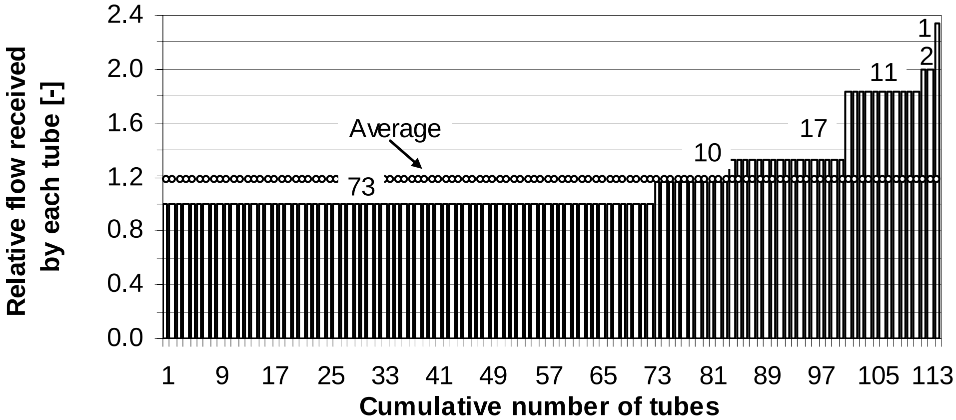


Figure 3-55: Proportion of relative flows going into the tubes for effect 2-5.

There were 114 tubes in this pass. Of them, 41 received significantly more than the average flow. 73 underfed tubes received 0.85 of the average flow.

Misdistribution in Effect 3

Figure 3-56 shows the misdistribution in effect 3.

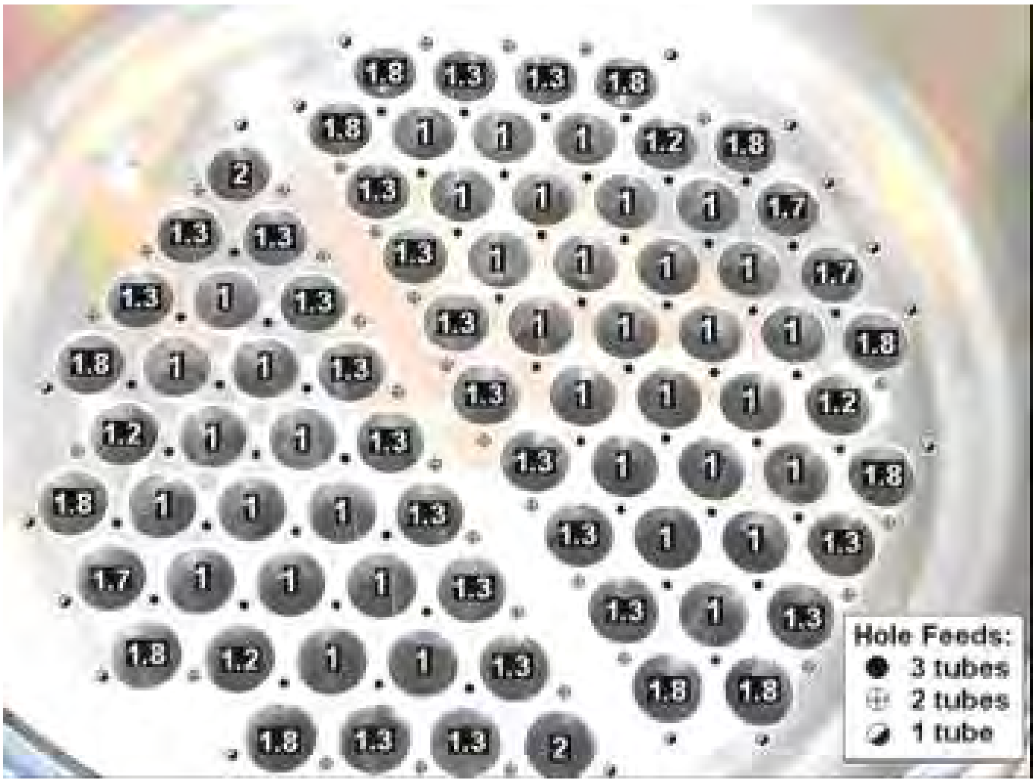


Figure 3-56: Relative flows into the tubes for effect 3.

Figure 3-57 shows the relative flow into each tube, cumulatively for all the tubes.

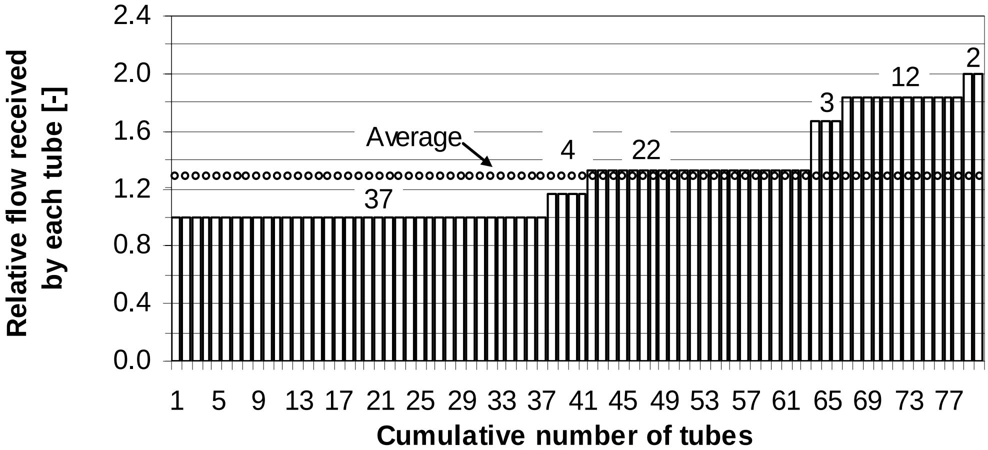


Figure 3-57: Proportion of relative flows going into the tubes for effect 3.

The tube split in effect 4 caused an unusually large number of tubes to be 'edge tubes.' There were 37 inner tubes and 43 edge tubes.

This created a much greater misdistribution than pass 5 of effect 2. 41 of the 80 tubes received a relative flow of 0.78 the average flow. 22 received the average relative flow, and 17 received considerably more than the average flow.

Misdistribution in Effect 4

Figure 3-58 shows the misdistributions in effect 4. Figure 3-59 shows the relative flow into each tube, cumulatively for all the tubes.

Figure 3-58: Relative flows into the tubes for effect 4.

The tube split in effect 4, like effect 3, caused an unusually large number of tubes to be 'edge tubes.' The misdistribution in effect 4 is similar to effect 3. 47 tubes received 0.79 of the average flow, 29 tubes received approximately the average flow and 20 tubes received considerably more than the average flow. The larger number of tubes in effect 4 and the smaller liquid flowrates meant that the impact of misdistribution on wetting in effect 4 was much more serious than the misdistribution in effect 3.

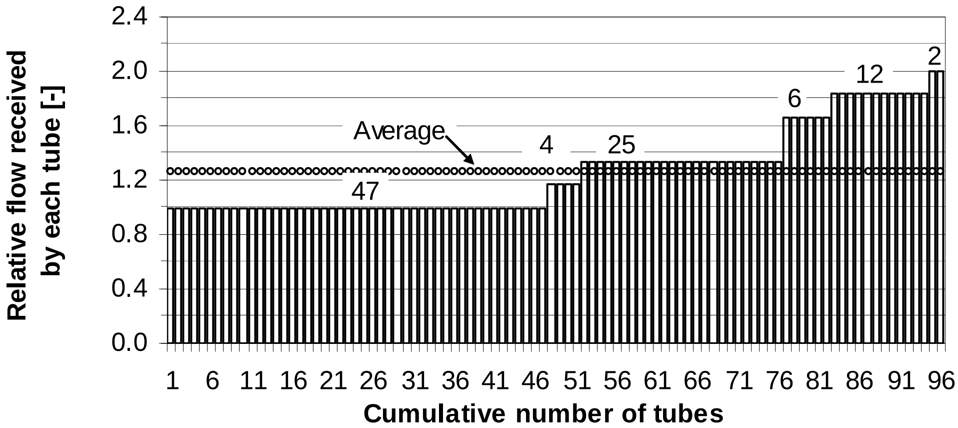


Figure 3-59: Proportion of relative flows going into the tubes for effect 4.

3.3.6 Wetsuit Job

The wetsuit job was performed on 27 July 2004 on Evaporator 4. The Niro distribution plates and the model acrylic plates were tested in effects 3 and 4. Water was poured into the distribution section, and the outlet flowrates of water were measured from specific tubes. Three replications were made for each tube.

Niro Distribution Plates

Figure 3-60 and Figure 3-61 show the expected and measured relative flows into the sampled tubes for effects 3 and 4.

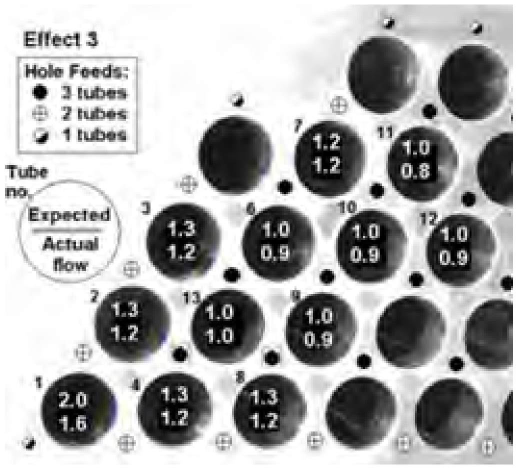


Figure 3-60: The expected and measured relative flows into tubes using Niro's effect 3 distribution plate in Evaporator 4.

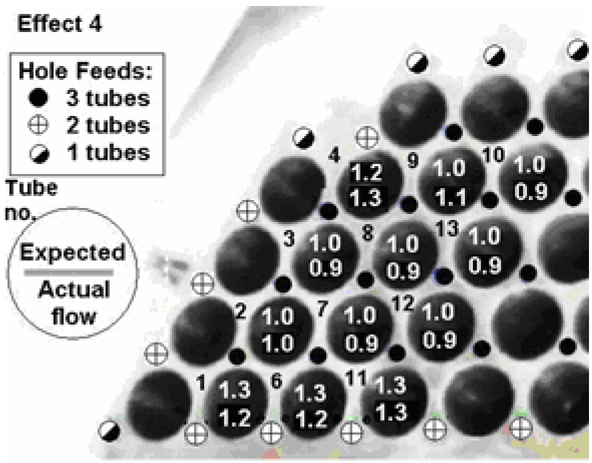


Figure 3-61: The expected and measured relative flows into tubes using Niro's effect 4 distribution plate in Evaporator 4.

These figures confirm that the Niro distribution plates caused liquid misdistributions. The edge tubes received up to 1.6 times the flow of other tubes. The inner tubes received significantly less liquid than the edge tubes, confirming the predicted misdistribution in the holes-tubes analysis.

Table 3-17 shows the mass flowrates measured for the tubes in effects 3 and 4.

Table 3-17: The mass flows and relative flows entering the tubes in effects 3 and 4 of Evaporator 4 with the existing Niro distribution plates.

Tube	Effect 3		Effect 4	
	Flow in $g\ s^{-1}$	Relative Flow [-]	Flow in $g\ s^{-1}$	Relative Flow [-]
Flow in one hole	33 ± 1	1.0 ± 0.1	26 ± 1	1.0 ± 0.1
1	52	1.6	31	1.2
2	40	1.2	25	1.0
3	39	1.2	22	0.9
4	40	1.2	35	1.3
5	–	–	–	–
6	31	0.9	32	1.2
7	39	1.2	22	0.9
8	40	1.2	23	0.9
9	30	0.9	28	1.1
10	30	0.9	23	0.9
11	26	0.8	34	1.3
12	30	0.9	24	0.9
13	33	1.0	23	0.9

The tube labels are shown from Figure 3-60 and Figure 3-61. There was considerable variation in the flowrates into the tubes. The flowrates varied from 26 to 52 $g\ s^{-1}$ in effect 3 and from 22 to 35 $g\ s^{-1}$ in effect 4. Refer to Appendix A-5 for more information.

Acrylic Distribution Plates

The model distribution plates surrounded each tube with six holes and the hole sizes were calculated to give equal flows into each tube. Figure 3-62 and Figure 3-63 show the expected and measured relative flows in effects 3 and 4. Table 3-18 shows the flowrates measured from each sampled tube.

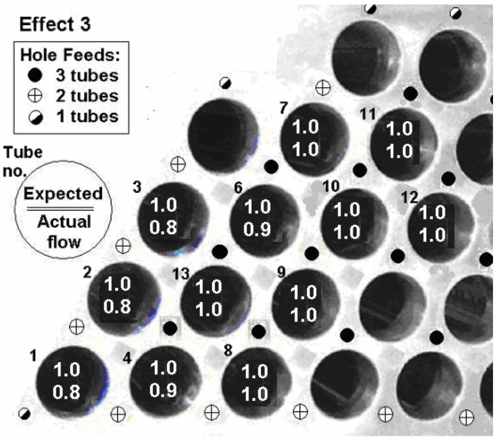


Figure 3-62: The expected and measured relative flows into tubes for the acrylic model distribution plate in effect 3.

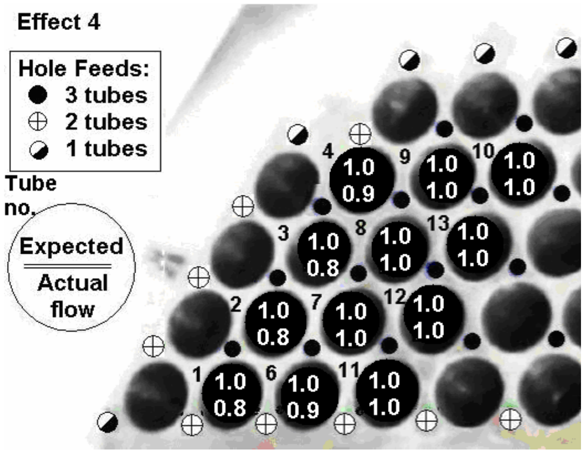


Figure 3-63: The expected and measured relative flows into tubes for the acrylic model distribution plate in effect 4.

Table 3-18: The mass flows and relative flows entering and exiting the tubes in effects 3 and 4 with the existing acrylic distribution plates in Evaporator 4.

Tube	Effect 3		Effect 4	
	Flow in g s^{-1}	Relative Flow [-]	Flow in g s^{-1}	Relative Flow [-]
Average flow into one tube	33 ± 1	1.0 ± 0.1	26 ± 1	1.0 ± 0.1
1	30	0.8	29	0.8
2	31	0.8	30	0.9
3	32	0.8	36	1.0
4	34	0.9	48	1.4
5	–	–	–	–
6	36	0.9	30	0.6
7	37	1.0	35	1.0
8	39	1.0	36	1.0
9	37	1.0	35	1.0
10	38	1.0	34	1.0
11	37	1.0	33	0.9
12	39	1.0	36	1.0
13	38	1.0	34	1.0

The acrylic distribution plates had a near-perfect liquid distribution. The tubes on the edge of the tubesheet had slightly less liquid than the ones at the inside. This is likely to be because the flows through the smaller holes were lower than expected.

This investigation showed that correctly designing the hole sizes in a distribution plate can give a proper liquid distribution. The hole sizes in the current distribution plates in effect 4 should be modified to give better liquid distributions.

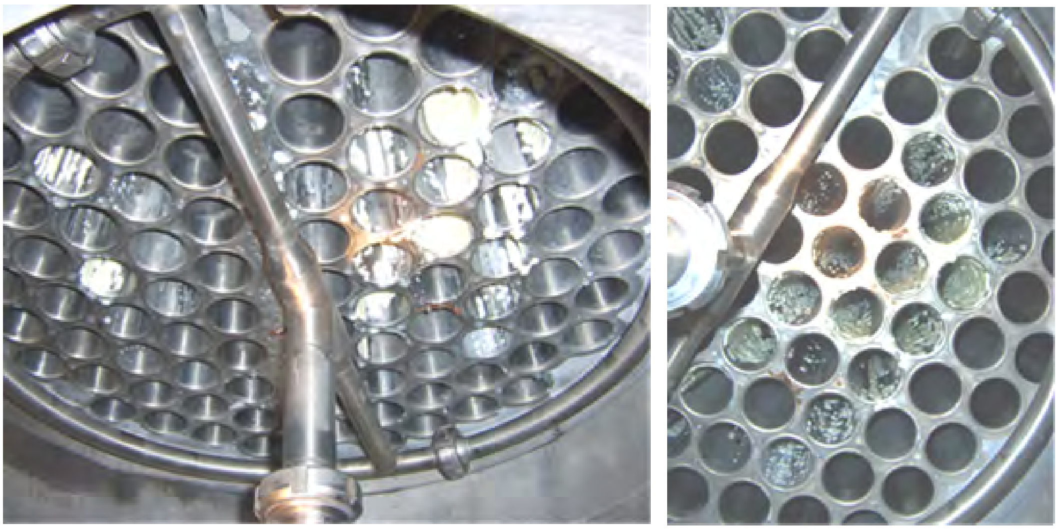
It may be argued that the hole sizes are sized to give more milk to the outside tubes because of the flow of flash vapours from the top of the calandria to the tubes. For example in effect 4 of Evaporator 3 on 27 January 2005, approximately 112 kg h^{-1} of flash evaporation gave 0.37 m^3 s^{-1} of vapour travelling at 6.7 m s^{-1} through the gap between the distribution plate and the tubesheet. This is a significant vapour flow. However, having large hole sizes does not ensure that the tubes are fully wet with equal amounts of milk. In this case the distribution plate should be raised and hole sizes changed to give equal flows of milk to each tube.

3.3.7 Opening an Evaporator before Cleaning – Whole Milk

Observations

Effects 3 and 4 of Evaporators 1 and 2 were opened immediately after a 22-hour run of whole milk on 26 May 2004. The tubes had been rinsed with water but had not been cleaned. The top of the tubes were all extremely clean although there were a few occasional blocked holes in the distribution plates. The underside of the spray plates were dirty except for clean spots which surrounded holes. These spots had diameters of approximately 15 mm.

Figure 3-64a and Figure 3-64b show the fouling viewed at the bottom of effect 4 in Evaporator 2. They show that the misdistribution in effect 4 was sufficient to cause fouling. There were 26 dirty tubes. Of them, 15 were significantly fouled. These tubes were mostly ‘inner’ tubes of the apparent passes, although some tubes were next to the tube split. The evaporators were run at flowrates recommended by Niro.



(a) (b)

Figure 3-64 a and b: Fouling in Evaporator 2 effect 4 after a 22 hour whole milk run.

Figure 3-65 shows the bottom of effect 4 in Evaporator 1. It was run identically to Evaporator 2, but had much less fouling. Two of the five dirty tubes were significantly fouled. These were both 'inner' tubes. Effects 3 of Evaporator 1 and 2 were both immaculately clean, as shown in Figure 3-66. More photographs appear in Appendix A-13.1.

Figure 3-65: Fouling in Evaporator 1 effect 4 after a 22-hour whole milk run.

Figure 3-66: Evaporator 1 effect 3 after a 22-hour whole milk run.

Approximate Minimum Wetting Rates

Table 3-19 shows the experimentally measured wetting rates in and out of the underfed tubes in effects 3 and 4 at the end of the run. These were based on total solids measurements taken at the end of the run. The measurements indicate the approximate minimum wetting rates of whole milk was approximately 0.18 kg $m^{-1}s^{-1}$.

Table 3-19: The wetting rates and total solids in and out of the underfed tubes in effects 3 and 4 of Evaporators 1 and 2.

Evaporator & Pass	Total Solids %	Wetting Rate kg $m^{-1}s^{-1}$	Comments
Evaporator 1			
Into effect 3	42.7	0.242	Clean.
Out of Effect 3	46.0	0.225	Clean.
Into Effect 4	46.0	0.189	Clean.
Out of Effect 4	49.9	0.175	5 fouled tubes.
Evaporator 2			
Into effect 3	42.0	0.244	Clean.
Out of Effect 3	46.6	0.220	Clean.
Into Effect 4	46.6	0.186	Clean.
Out of Effect 4	52.3	0.165	25 fouled tubes.

Improvements to Operation

Clearly, the wetting rates in effect 4 were inadequate to fully wet the tubes. The three methods to increase the wetting rates were to improve the liquid distribution, to increase the flowrates or to reduce the surface area.

Improving the distribution plate design will give the tubes equal amounts of liquid. Increasing the feed flowrates has been met with resistance by staff because of dryer constraints. This is particularly so in CD1 because the cyclones were prone to blocking.

Staff at Fonterra Clandeboye are keen to permanently block some tubes in order to reduce the surface area. Considerable evaporation area was lost during the whole milk run due to the formation of fouling. An estimation of the area is shown in Table 3-20. It was assumed that the fouling coated the wall surface for half the length of every fouled tube and was thick enough to prevent evaporation on the surface.

Table 3-20: The estimated surface area occupied by fouling in effect 4.

Variables	Effect 4 for Evaporator: 1	2	Units
Number fouled tubes	5	26	–
Fouling area	5.3	27.5	m^2
Area of single tube	2.1	2.1	m^2
Equivalent number of fouled tubes	2.5	13.0	–

The table shows that Evaporator 1 would perform as effectively if two or three tubes were blocked. Evaporator 2 would perform as efficiently if 13 tubes were blocked.

3.3.8 Opening an Evaporator before Cleaning – MPC-85

Observations

Evaporator 4 was opened after a run of MPC-85. It was specification 66-4853 on 5 April 2005. The evaporator had been running for 5 hours under 3-effect mode. It was rinsed with water but had not been cleaned. The top and bottom of effects 2, 3 and 4 were inspected. Logbooks gave the approximate running conditions. Photographs appear in Appendix A-13.3 for this run and Appendix A-13.2 shows a run observed after cleaning on 29 September 2004.

Table 3-21 summarises the cleanliness of the top and the bottom of the tubes and of the distribution plates. The evaporator was very dirty because there was no filter between the 3-effect DSI and effect 2. This allowed *burnt chunks* from the DSI to enter effect 2 and block many distribution plate holes.

Table 3-22 shows the number of fouled tubes in each pass. An estimate was made for the number of totally fouled tubes in each pass.

Many burnt chunks from the DSI lodged in the distribution plate holes in pass 1. Foam is likely to have transported some burnt chunks to passes 2 and 5. Consequently, some tubes in these passes received less liquid and fouled.

There was a blocked tube in pass 5 of effect 2. This gave characteristic white spongy chunks in the distribution plate of effect 3. The distribution plate hole blockages caused fouling at the top of some tubes in effect 3. Fortunately, the wetting rates were sufficient to give full wetting at the bottom of all the tubes. The tubes in effect 4 were clean at the top and bottom, indicating that the wetting rates were sufficient to fully wet the tubes.

Table 3-21: Summary of the cleanliness of Evaporator 4 after 5 hours of MPC-85.

Effect & Pass	Distribution Plate	Top of tubesheet	Bottom of tubesheet
2-1	Many DSI chunks.	9 mildly fouled.	7 fouled tubes.
2-2	Many DSI chunks.	4 fouled tubes.	17 fouled tubes.
2-3	Some holes blocked.	20 fouled tubes.	1 fouled tube.
2-4	A few DSI chunks.	14 fouled tubes.	No fouled tubes.
2-5	Many DSI chunks.	15 fouled tubes. 1 blocked tube.	A few fouled tubes. 1 blocked tube.
3-1	Many spongy chunks.	12 fouled tubes.	No fouled tubes. Spotless.
4-1	A few spongy chunks.	No fouled tubes.	No fouled tubes. Protein build-up on tube split.
4-1*	Mostly clean.	No fouled tubes.	Extensive build-up on tube split.

**Evaporator 3 viewed after two poor cleans, done with suspected poor caustic soda.*

Table 3-22: Equivalent number of tubes fouled in each pass.

Effect – Pass	Tubes fouled at: Top	Bottom	Estimated number of fouled tubes	Fouled tubes in pass %
2-1	9	7	8	3
2-2	4	17	10.5	4
2-3	20	1	10.5	5
2-4	14	–	7	5
2-5	15	5	10 (+ 1 blocked)	10
Total effect 2	–	–	47	4
Total effect 3	12	–	6	8
Total effect 4	–	–	0	–

Minimum Wetting Rates

Little is known about the minimum wetting rates of MPC-85. Table 3-23 shows the wetting rates in each pass. Only tubes underneath blocked distributor holes were fouled. Unfortunately, it is difficult to estimate the wetting rates into the dirty tubes.

The wetting rates were high enough to fully wet the tubes, provided there were no blocked holes. Some tubes in effect 3 received liquid from only one or two holes due to blockages. They were fouled at the top, but despite the distribution problems the flows were sufficient to fully wet the tubes partway down the tubes. It is unclear how much liquid entered these tubes.

Table 3-23: Summary of the wetting rates for clean tubes in Evaporator 4 after 5 hours of MPC-85 production.

Effect–Pass	Estimated total solids %	Wetting Rate kg $m^{-1}s^{-1}$
In 2-1	15.0	0.123
Out of 2-5	24.3	0.204
Into 3-1	24.3	0.269
Out of 3-1	25.0	0.261
Into 4-1	25.0	0.220
Out of 4-1	25.7	0.214

Installation of a Filter

A filter between the 3-effect DSI and effect 2 would reduce amount of burnt chunks entering the evaporator. The benefits of installing a filter are listed as follows:

- Less cleaning chemicals would be required to dissolve chunks lodged in the holes.
- The reduction in chunks in the distribution plates will reduce tube fouling during a run. This will reduce cleaning time and chemical use.
- Fouled tubes occur underneath blocked holes. The cleaning chemicals must dissolve the chunks before fouled tubes can be cleaned. As there will be fewer chunks lodged in the distribution plate holes, there will be a shorter cleaning time.
- Blocked tubes occur when fouled tubes cannot be fully cleaned. Blocked distribution plate holes are again the likely cause. A filter will reduce chunks lodging in holes and reduce tube blockages.

Burnt Chunks and Fouling

Fonterra staff had to sometimes manually remove fouling prior to a chemical clean in order to bring the evaporators to a visually acceptable cleanliness. Figure 3-67 shows burnt chunks deposited in the distribution plate of effect 2 pass 1. Figure 3-68 shows the fouling at the top of effect 3, caused by blocked distributor holes. The blocked tube in pass 5 of effect 2 is shown in Figure 3-69. Figure 3-70 shows some fouling observed at the bottom of effect 4 in Evaporator 3 after poor cleaning.

Figure 3-67 shows there were many burnt chunks in the pass 1 distribution plate of effect 1. There was also fouling on the outside of the deflector basket due to excessive foaming. This foaming probably allowed burnt chunks to overflow into passes 2 and 5, blocking some of the distribution plate holes.

Although Figure 3-68 shows there was fouling at the top of effect 3 due to blockages in the distribution plate holes there was no fouling at the bottom of effect 3. It is unclear how the tube fully wet.

The blocked tube in pass 5 shown in Figure 3-69 is suspected to have created white spongy chunks which blocked the distribution plate holes in effect 3. Operators use these spongy chunks as an indicator of blocked tubes. This material was very tough and it was difficult to remove.

The fouling shown in Figure 3-70 was on the bottom of the tubesplit in effect 4 of Evaporator 3. It was very frustrating because it was tough and the evaporator had already been cleaned twice. The evaporator had to be chemically cleaned again after the fouling was manually removed.

Figure 3-67: Niro did not install a DSI filter so burnt chunks would lodge in the distribution plate. This has been fixed.

Figure 3-68: Blocked holes would cause fouling at the top of tubes. This has been corrected. The tube bottoms were clean.

Figure 3-69: A blocked tube in a Niro evaporator.

Figure 3-70: The two-pass design on the single-pass effect 4 allowed fouling to build up on the tube split.

3.3.9 Blocked Tubes in Effect 4

Figure 3-71 shows the position of four blocked tubes found in effect 4 of Evaporator 2. This was after a month of skim milk production. It is not known how long the tubes had been blocked.

Figure 3-71: Positions of blocked tubes in Evaporator 2 effect 4 after a month of skim milk production.

The blocked tubes were all inner tubes. Evaporator 1 was operated similarly to Evaporator 2 but it did not have tube blockages. This could be due to the small hole sizes in Evaporator 2. The distribution plates on Evaporators 1 and 2 commonly overflowed while processing skim milk. This may have caused the inner tubes in Evaporator 2 to receive less liquid than the equivalent tubes in Evaporator 1.

3.3.10 Revision of Wetting Equation

The distribution plate design must be considered when calculating the wetting rates in tubes. Calculations must be for the tubes in a pass at the conditions that are most likely to cause dry patches. In the case of a misdistribution, the calculations must be done for tubes which receive the least liquid. In a personal communication (2005) Tony Mackereth mentioned that the minimum exit liquid loadings are to be used for design purposes, as the lowest wetting rate in a tube is at the bottom. The dairy industry needs to be more aware of this.

In Niro's distribution plates, the inner tubes of a pass received the equivalent flow of liquid from one hole. This means it is the number of holes in the distribution plate, as well as the number of tubes in the tubesheet, which determines the actual wetting rate into and out of the tubes.

The wetting equation has been modified to include the number of holes in the distribution plate and the outlet flowrate from a tube. $\Gamma_{low,\ out}$ is the wetting rate out of underfed tubes, which have the lowest wetting rates in the pass. The $\dot{m}_{out}$ is the mass flowrate of liquid out of the pass. This is similar to Equation 1, but replaces n_{tubes} with n_{holes}.

$$\Gamma_{low,out} = \frac{\dot{m}_{out}}{n_{holes}\,\pi\, d_i} \qquad \textbf{(26)}$$

Note that the number of holes is similar to the number of tubes for Niro distribution plates. This is because one hole feeds three tubes and one tube is fed by three holes, giving an approximate ratio of holes to tubes of 1:1. For Stork distribution plates one hole feeds three tubes and each tube is fed by six holes, giving a holes-to-tubes ratio of approximately 2:1. Thus the distribution plate design must be very carefully considered when evaluating wetting rates.

3.3.11 Misalignment

Misalignment affects liquid distribution. Slight misalignment can position a hole closer to one tube than others, preferentially feeding one side of the tubes. At worst, the liquid can pour directly down the tube with little contact to the tube surface. There was slight misalignment of a few millimetres in many effect 3 and 4 distribution plates but this had no observable impact on the operation. Misalignment was less critical for effect 3, as the tube pitch was larger, making it easier for milk rivulets to spread across the tubesheet. Figure 3-72 and Figure 3-73 show the importance of alignment on good liquid distribution.

Several passes were misaligned, especially in effect 2. In Edendale's Evaporator 7 the holes in pass 2 of effect 2 were misaligned, as Figure 3-74 illustrates. A thin vernier calliper was pushed directly down the nearest tube while the tool was nearly vertical

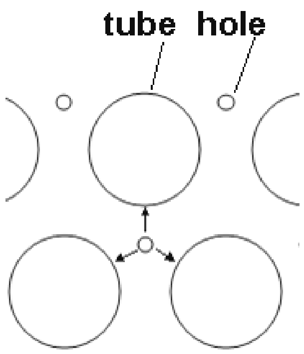


Figure 3-72: Perfectly aligned holes give liquid evenly to all surrounding tubes.

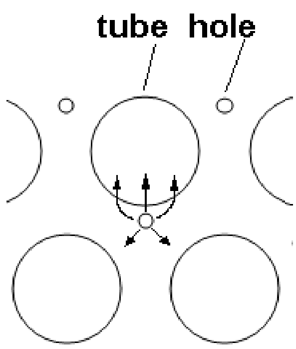


Figure 3-73: Misaligned holes have a preferential flow to one tube. This may hinder the formation of a complete film.

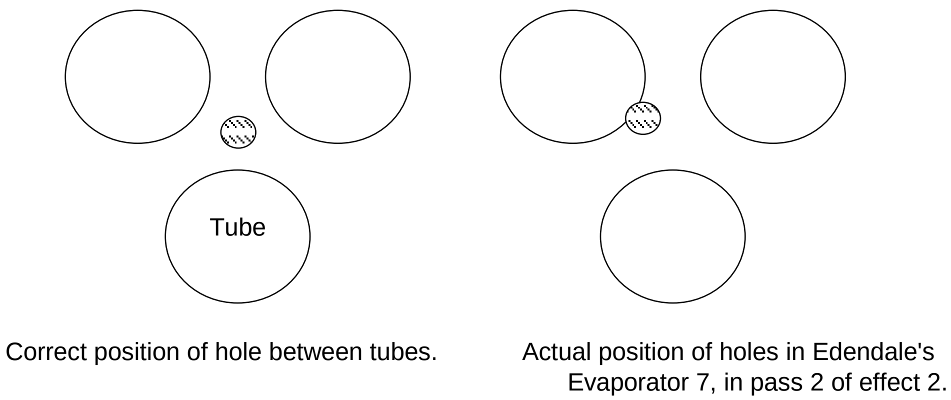


Figure 3-74: The correct position of holes between tubes (left), and the actual position of misaligned holes in Edendale's Evaporator 7 in pass 2 of effect 2 (right).

Appendix A-6 has a complete list of hole misalignment faults found in the Clandeboye and Edendale evaporators.

3.3.12 Warping

Warping is when the distribution plate somehow buckles, preventing it from being perfectly flat and level. A variation in the height of the distribution plate above the tubesheet indicates warping. For this project, a distribution plate with a height variation of 4 mm or more was considered warped. Figure 3-75 shows that variations in the height of the distribution plate above the tubesheet causes different liquid head heights.

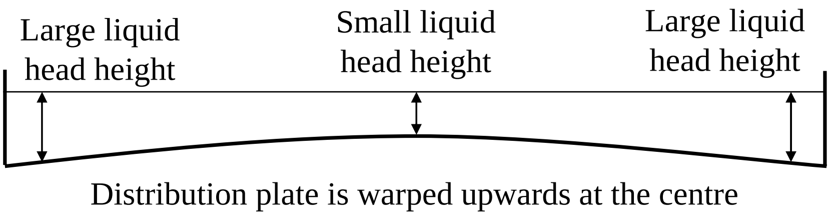


Figure 3-75: Warping of the distribution plates causes a variation in the liquid head heights across the distribution plate.

The passes which had significant warping are shown in Figure 3-76. This covered the Edendale and Clandeboye evaporators. Appendix A-6 contains a comprehensive list of measurements for the evaporators. The error bars show the variation in the height of the distribution plate above the tubesheet. The points show the average height of the distribution plate above the distribution plate.

The small distribution plates in effects 3 and 4 had some warping. The large distribution plates were more affected by warping. There was serious warping in effect 2 of Evaporators 1 and 2. The gap was large enough to pass a finger through. Strangely, the warping only happened between passes 1 and 5. Figure 3-77 shows the heights measured from the top of the distribution plate to the tubesheet. Figure 3-78 and Figure 3-79 show the measurements made on the distribution plates.

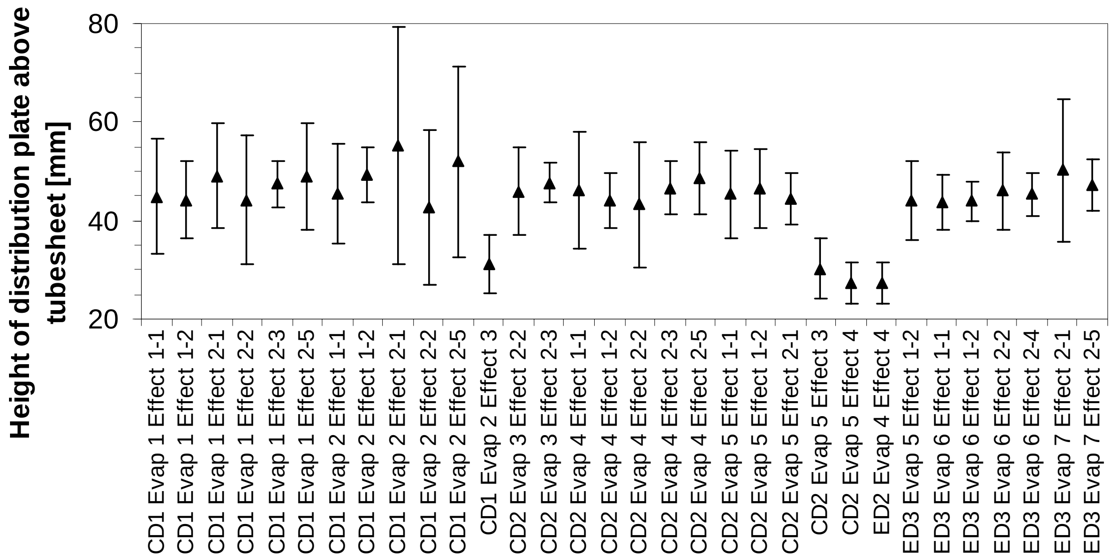


Figure 3-76: The points show the height of warped distribution plates above the tubesheet in the evaporators. The error bars show the maximum and minimum heights for each plate.

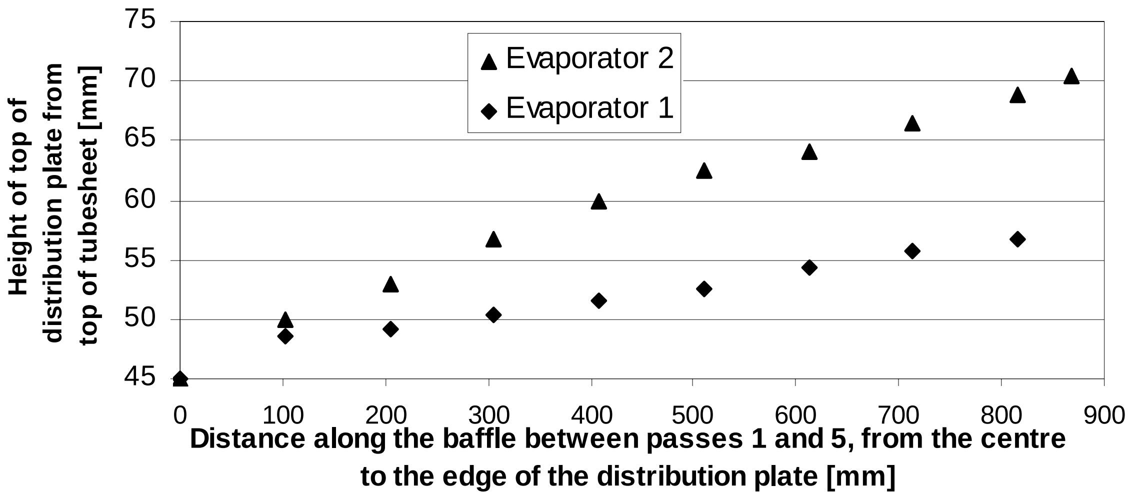


Figure 3-77: Height of the top of the distribution plate from the top of tubesheet, radially along the baffle between passes 1 and 5.

Figure 3-78: The height of the top of the distribution plate above the tubesheet for pass 1 of effect 2 in Evaporator 1.

Figure 3-79: The height of the top of the distribution plate above the tubesheet for pass 1 of effect 2 in Evaporator 2.

This warping could lead to wetting problems in some tubes. The holes on the upraised sections had a lower liquid head height, giving the tubes less liquid. Whole milk operated with an approximate liquid head height of 60 mm in passes 1 and 5. Tubes in the ‘upraised’ areas were expected to receive 0.67 of the flowrate received by tubes under ‘unwarped’ sections. For skim milk with a typical liquid head height of 80 mm, the tubes under warped parts would have received approximately 0.74 the liquid received by unwarped sections. These tubes may not receive enough liquid to fully wet.

It is uncertain whether warping occurred during fabrication or over time. Communications between Ken Morison and Dr. John Smaill from the Department of Mechanical Engineering at the University of Canterbury indicate that sudden heating could cause relaxation of welding stresses and lead to warping. There was sudden heating of the tubes during start-up causing the base of the distribution plate to heat suddenly, while the vertical baffles stayed cooler and was heated by conduction. The warping in the effect 2 distribution plates suggests that this may have happened.

Niro has made no design measures to prevent warping in the distribution plates. They supply unrestrained plates which rest on a tubesheet, positioned by two pins. Figure 3-80 shows supports on the underside of the effect 1 distribution plate which are meant to stop the plate from sagging. Unfortunately, some distribution plates sagged between the supports.

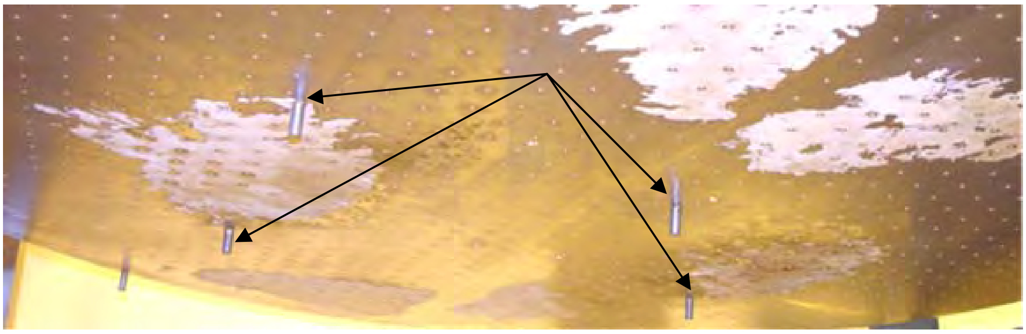


Figure 3-80: The effect 2 distribution plate has supports on the underside to prevent the plate from sagging.

The Stork design of distribution plates, while being fundamentally different to the Niro design, 'sandwiched' the distribution plate between the calandria lid and tubesheet. Some tubes were blocked off to provide supports for the distribution plate. No Stork distribution plates were investigated for warping.

3.3.13 Fabrication Faults

Appendix A-6 details the many fabrication faults found in the distribution plate of the Clandeboye and Edendale evaporators. Both Niro and Fonterra must improve their quality checking procedures. Examples include some holes being partially blocked by metal, warped plates and some passes having misaligned holes. Larger plates were affected more by warping and misalignment because of their size.

3.3.14 Conclusions

The tubesheets for effects 3 and 4 had a two-pass design, although they acted as single pass units. There were 80 tubes in effect 3 and 96 tubes in effect 4, even though the milk flowrates were lower in effect 4.

There were inconsistent hole sizes in some evaporator passes, particularly in effect 4 of Evaporators 1 and 2. Quality checking procedures by Niro and Fonterra must improve.

There were more holes than tubes in every pass.

There was a predicted misdistribution of liquid between tubes in every pass, particularly in effects 3 and 4. This is because of the distribution plate design. A water trial confirmed this.

Evaporators were inspected before cleaning. Tubes which received low flows of whole milk in effect 4 were fouled at the bottom. There was fouling at the top of tubes after five hours of MPC-85 production because large milk particles blocked some distribution plate holes, preventing liquid entering the underlying tubes. Installing a filter after the MPC DSI would prevent these particles entering the evaporator. The wetting rates of MPC-85 in the evaporator were sufficient to give full wetting.

Blocked tubes were observed after prolonged production of skim milk in Evaporator 2.

The evaluation of wetting rats must be done at the point at which the falling film is most likely to break up. This is at the base of the tubes which receive the least liquid.

Some distribution plate holes were slightly misaligned with the tubes, some holes were improperly drilled and the holes in some passes were drilled too small.

Some distribution plates were warped. This was a particular problem for the large distribution plates in effects 1 and 2. There were attempts to properly prevent the distribution plates from warping. The distribution systems must be designed better.

3.4 Total Solids Measurements

3.4.1 Overview

Milk samples were taken from the evaporators to find the total solids concentrations from each pass during typical operation. Evaporators 1 and 4 were studied in detail because they had full sets of sample points. Measurements were taken for skim milks, whole milks and MPC-85.

The following tasks were performed:

- The concentration of milk from each pass was profiled for each evaporator.
- The wetting rates were found out of each tube.
- The evaporation rates were calculated in each pass.
- The overall heat transfer coefficients (OHTC) were determined for each pass.
- The typical OHTC profile was displayed for Evaporators 1 and 4.
- Correlations were determined for the OHTC of skim and whole milks as a function of the average total solids concentration in a pass.

3.4.2 Skim Milk

Total Solids Profile

Figure 3-81 shows the typical total solids profile of skim milk exiting each pass in Evaporators 1 and 4, one hour after start-up at steady state.

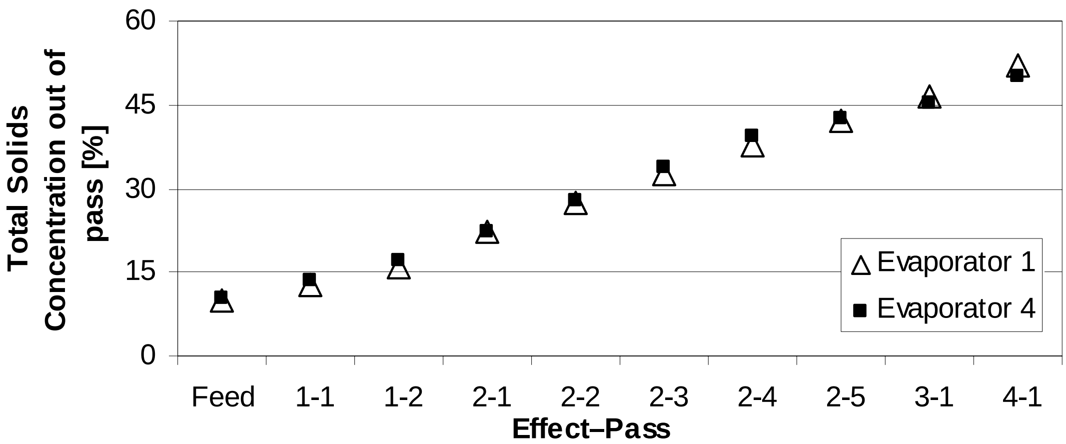


Figure 3-81: Typical total solids profiles of skim milk exiting each pass in Evaporators 1 and 4 one hour after start-up.

Calculated Wetting Rates

Figure 3-82 shows the outlet wetting rates for each pass. This was done for the inner tubes of the pass, which are 'underfed' compared to those at the edge. The minimum wetting rates are provided for skim milk under heat transfer and evaporation conditions from the wetting rig.

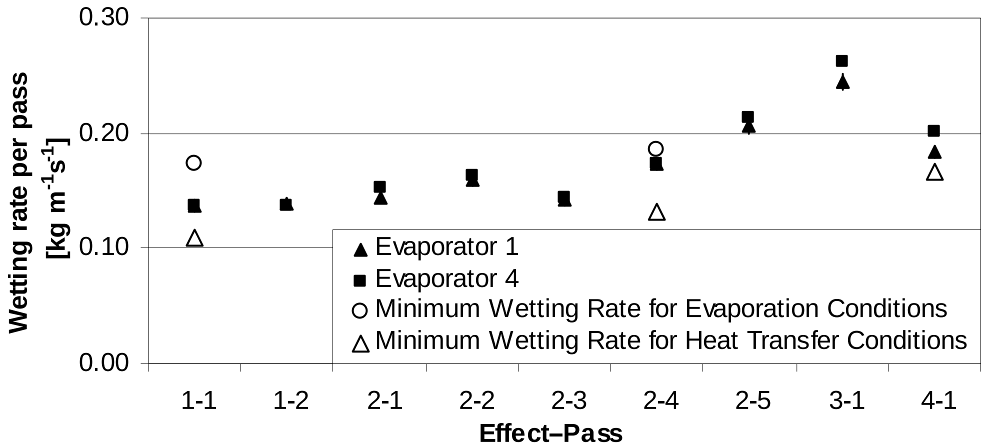


Figure 3-82: Typical outlet wetting rates of skim milk for the inner tubes of each pass in Evaporators 1 and 4. Minimum wetting rates are provided for evaporation and heat transfer conditions from the wetting rig.

The wetting rates out of pass 1 in effect 1, and from pass 5 of effect 2 were above the minimum wetting rates for heat transfer conditions but below those for evaporation conditions. It was unclear whether the tubes became fully wet.

The wetting rates out of the inner tubes in effect 4 were worrying. The minimum wetting rate was 0.166 kg $m^{-1}s^{-1}$ for 50% skim milk under heat transfer conditions, and 0.186 kg $m^{-1}s^{-1}$ for 40% milk under evaporation conditions. The calculated wetting rates were 0.184 kg $m^{-1}s^{-1}$ from Evaporator 1 and 0.201 kg $m^{-1}s^{-1}$ from Evaporator 4. These values were close to the minimum wetting rates.

The typical temperature differences in effect 4 ranged from 4 to 10ºC. This means nucleate boiling was more likely to occur. The minimum wetting rate for 50% skim milk under heat transfer conditions was expected to be between approximately 0.20 kg $m^{-1}s^{-1}$. It was unclear whether the tubes became fully wet.

Evaporation Rates

Figure 3-83 shows the typical evaporation rates for skim milk in each pass of Evaporators 1 and 4. The evaporators clearly operate differently in effects 1 and 2.

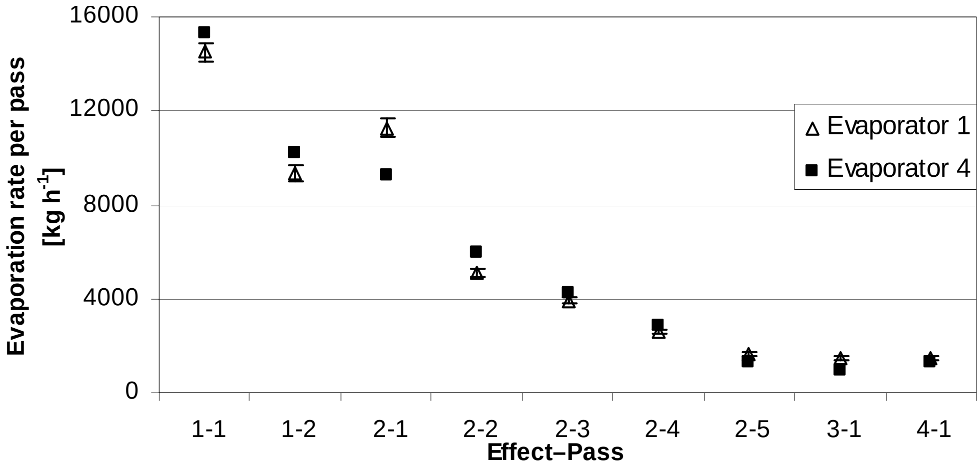


Figure 3-83: Evaporation rate in each pass for skim milk in Evaporators 1 and 4.

Evaporator 4 had a more predictable set of evaporation rates than Evaporator 1. In Evaporator 4 the evaporation rate decreased smoothly with every pass. The vapour flowrate was 10,200 kg h^{-1} in pass 2 of effect 1, and it was followed by 9,300 kg h^{-1} in pass 1 of effect 2. The vapour rates in Evaporator 1 were different. The evaporation rate in pass 2 of effect 1 was approximately 9,400 kg h^{-1}. The subsequent evaporation rate was 11,300 kg h^{-1} in pass 1 of effect 2.

Typical Overall Heat Transfer Coefficients (OHTCs)

Figure 3-84 shows the OHTC versus the average total solids concentration of skim milk along each pass of Evaporators 1 and 4. These were both sampled one hour after start-up, at steady state. Evaporator 4 had much larger error bars than Evaporator 4.

In Evaporator 1 the OHTC in pass 1 of effect 2 was unusually high, at 3266 W $m^{-2}K^{-1}$. A sensible maximum OHTC is 2500 W $m^{-2}K^{-1}$ for milk (James Winchester, personal communication, 2004). Previous total solids samples taken from Evaporator 1 by James Winchester showed a similar peak.

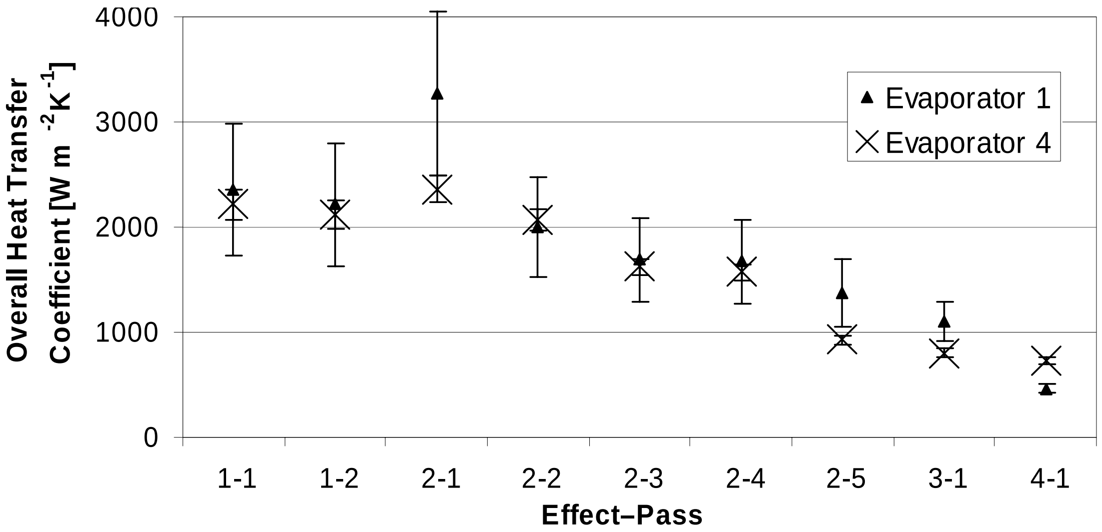


Figure 3-84: Typical overall heat transfer coefficient per pass for skim milk in Evaporators 1 & 4.

There were large uncertainties in the temperature sensors for Evaporators 1 and 2. These gave large uncertainties in the temperature differences and gave the large error bars on Figure 3-84. Evaporators 3, 4 and 5 had much smaller uncertainties in temperature readings, giving more accurate OHTCs.

The OHTC in Evaporator 4 decreased linearly from a value of 2213 W $m^{-2}K^{-1}$ in pass 1 of effect 1 to 722 W $m^{-2}K^{-1}$ in effect 4.

All OHTCs Measurements

Figure 3-85 shows the OHTCs versus the outlet total solids concentrations for skim milk in Evaporators 1 and 4.

The OHTC decreased approximately linearly through the passes. Note that the total solids and temperature were reversely correlated: as the total solids increased the temperature decreased. There were low OHTC values for total solids of approximately 40% to 44%. This was most likely caused by inaccuracies in total solids measurements for milk concentrate and inaccuracies in the temperature differences.

Skim Milk OHTC Equation

An equation was fitted for the OHTC of skim milk versus the total solids concentration from each pass. It was based on the entire sample set in Figure 3-85. The *TS* is the total solids of the skim milk exiting the pass. The equation is valid for milk exiting the pass from 11% to 50% total solids. The high OHTC values in pass 1 of effect 2 (20% TS) were unrealistically high and were ignored for the correlation.

The temperature in effect 1 was approximately 70ºC, effect 2 was approximately 65ºC, effect 3 was approximately 60ºC and effect 4 was 48ºC to 50ºC.

$$U_{skim} = -5463\,TS + 3247 \quad \textbf{(27)}$$

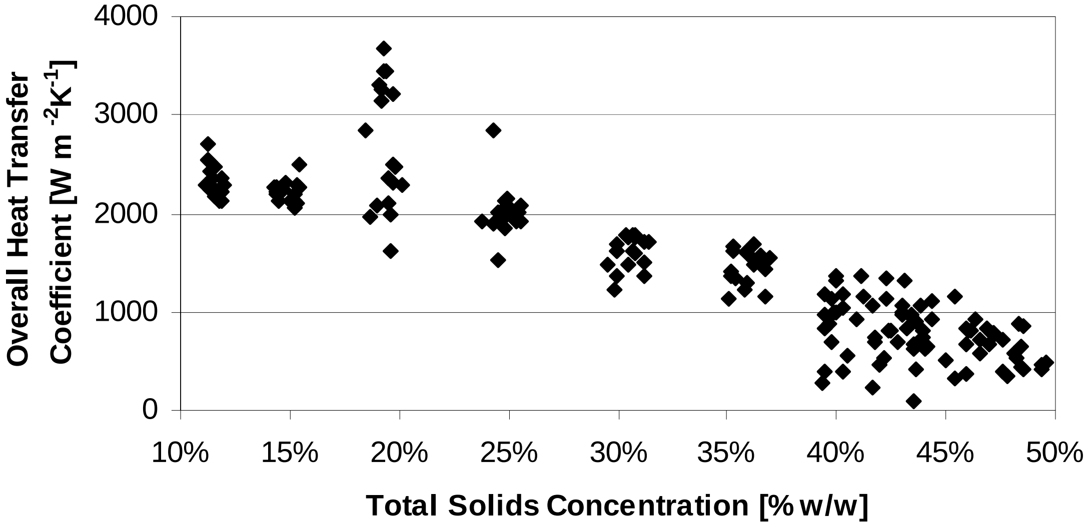


Figure 3-85: Overall heat transfer coefficients (OHTCs) versus the outlet total solids concentrations for skim milk from every pass of Evaporators 1 & 4.

3.4.3 Whole Milk

Total Solids Profile

Figure 3-86 shows the typical total solids of skim milk exiting each pass in Evaporators 1 and 4 at steady state, one hour after start-up.

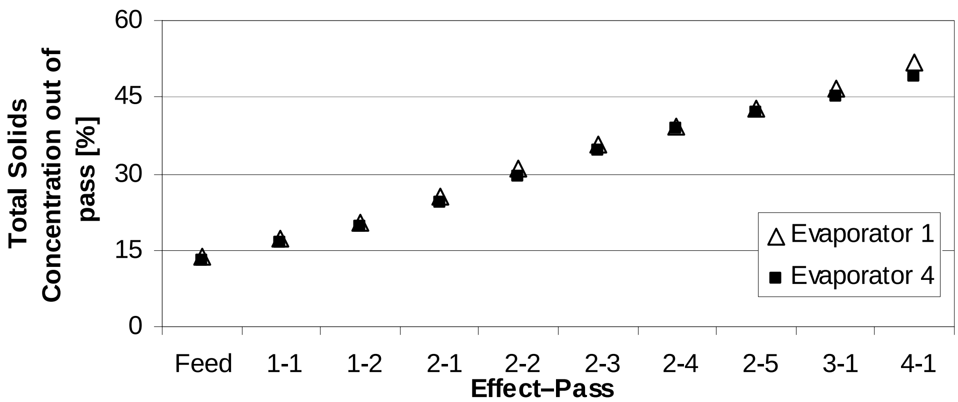


Figure 3-86: Typical total solids profiles of whole milk exiting each pass in Evaporators 1 and 4 one hour after start-up.

Calculated Wetting Rates

Figure 3-87 shows the wetting rates for the inner tubes in each pass. The minimum wetting rates were provided for whole milk under heat transfer conditions and under evaporation conditions.

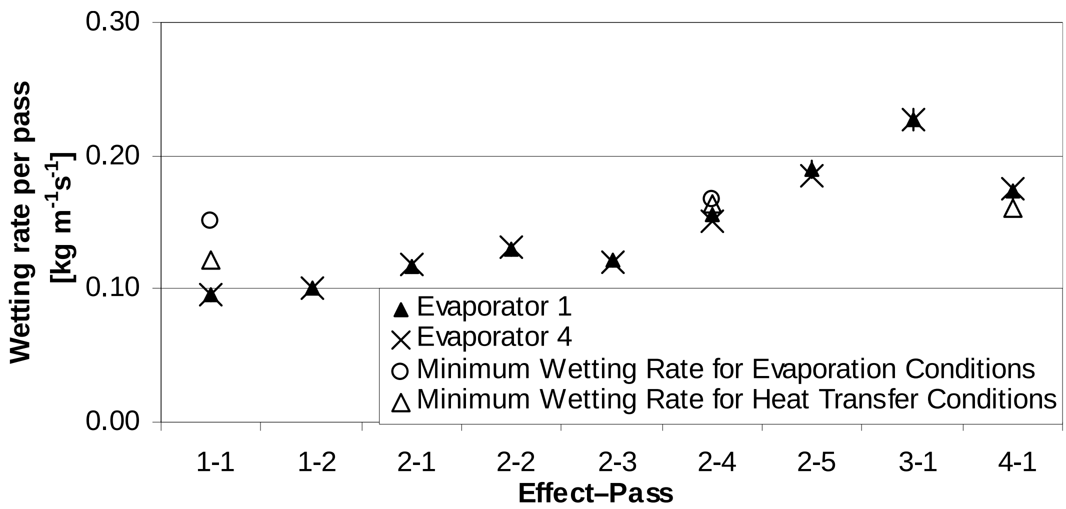


Figure 3-87: Typical outlet wetting rates of whole milk for the inner tubes of each pass in Evaporators 1 and 4. Minimum wetting rates are provided for evaporation and heat transfer conditions in the wetting rig.

The wetting rates out of passes 1 and 2 in effect 1 were below the minimum wetting rates for evaporation and heat transfer conditions. The wetting rates were 0.095 kg $m^{-1}s^{-1}$ in pass 1 and 0.101 kg $m^{-1}s^{-1}$ in pass 2. The minimum wetting rates were 0.121 kg $m^{-1}s^{-1}$ for heat transfer conditions and 0.151 kg $m^{-1}s^{-1}$ for evaporation conditions. It is unclear whether the tubes fully wet.

Niro's website indicates that special design considerations must be made for evaporators that process both skim and whole milks. Without due care in designing, the wetting rate in effect 1 can be too low for whole milk (Niro, 2004). This is because of the higher total solids content and lower feed flowrates of whole milk compared to skim milk.

The wetting rate out of pass 5 in effect 2 was slightly below the minimum wetting rates for heat transfer and evaporation conditions. The calculated wetting rate were both approximately 0.151 kg $m^{-1}s^{-1}$. The minimum wetting rates were 0.164 kg $m^{-1}s^{-1}$ for heat transfer conditions and 0.167 kg $m^{-1}s^{-1}$ for evaporation conditions. It is unclear whether the tubes fully wet.

The wetting rates out of the underfed tubes in effect 4 were a concern. The calculated outlet wetting rates were 0.173 kg $m^{-1}s^{-1}$ in Evaporator 1 and 0.175 kg $m^{-1}s^{-1}$ in Evaporator 4. The minimum wetting rate for 50% whole milk under heat transfer conditions was 0.160 kg $m^{-1}s^{-1}$. The minimum wetting rate for 40% whole milk under evaporation conditions was 0.167 kg $m^{-1}s^{-1}$. The minimum wetting rate of 50% whole milk was approximately 0.18 kg $m^{-1}s^{-1}$ (p. 81). It was unclear whether all the effect 4 tubes became fully wet.

Evaporation Rates

Figure 3-88 shows the evaporation rate of whole milk in each pass of Evaporator 1 and 4 in contrast to skim milk. The evaporators operated very similarly with whole milk. The peak was much smaller than the one observed while processing skim milk.

Typical Overall Heat Transfer Coefficients (OHTCs)

Figure 3-89 shows the OHTCs for each pass in Evaporators 1 and 4. There were very large uncertainties in most OHTCs which were caused by poor temperature measurements in effects 1 and 2. Evaporator 1 had a much lower OHTC in effect 4 than Evaporator 4. The OHTC for Evaporator 1 was 465 W $m^{-2}K^{-1}$ while it was 722 W $m^{-2}K^{-1}$ in Evaporator 4. There was again an unrealistically high OHTC in pass 1 of effect 2 in Evaporator 1.

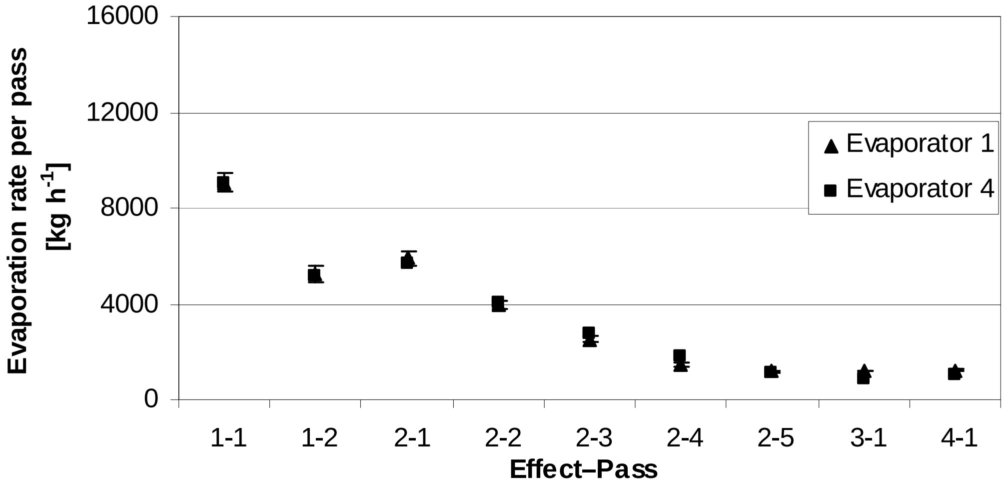


Figure 3-88: Evaporation rate of whole milk per pass in Evaporators 1 and 4.

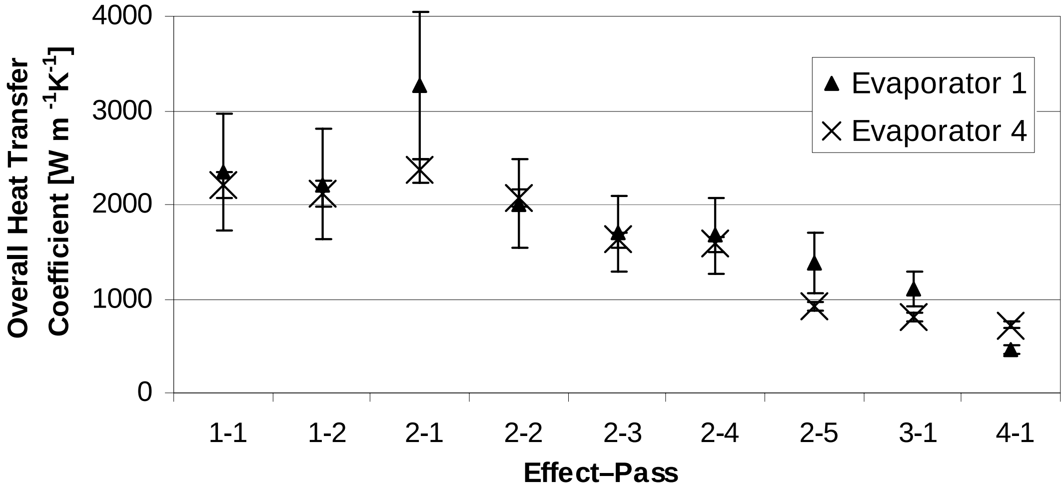


Figure 3-89: OHTC at start and end of run for whole milk in Evaporator 1.

All OHTC Measurements

Figure 3-90 shows the OHTCs versus outlet total solids concentration from each pass for whole milk in Evaporators 1 and 4.

The OHTCs in effects 2, 3 and 4 decreased approximately linearly through the evaporator. The OHTCs in effect 1 were surprisingly low. They were expected to be approximately 2500 W $m^{-2}K^{-1}$. Instead, they ranged from approximately 1300 to 2500 W $m^{-2}K^{-1}$. Figure 3-87 shows that the wetting rates in effect 1 were below the minimum wetting rates for heat transfer and evaporation conditions. Incomplete wetting may have caused the low OHTCs.

There were slightly lower OHTCs between 33% and 37% whole milk. This was for milk in pass 3 of effect 2 of Evaporator 1. Figure 3-87 shows that the outlet wetting rate from pass 3 was lower than passes 2, 4 and 5. Pass 3 had a wetting rate of 0.120 kg $m^{-1}s^{-1}$, while passes 2 and 4 had wetting rates of 0.131 kg $m^{-1}s^{-1}$ and 0.151 kg $m^{-1}s^{-1}$ respectively. The wetting rate in pass 3 may have been too low for complete wetting, lowering the evaporating area and OHTC.

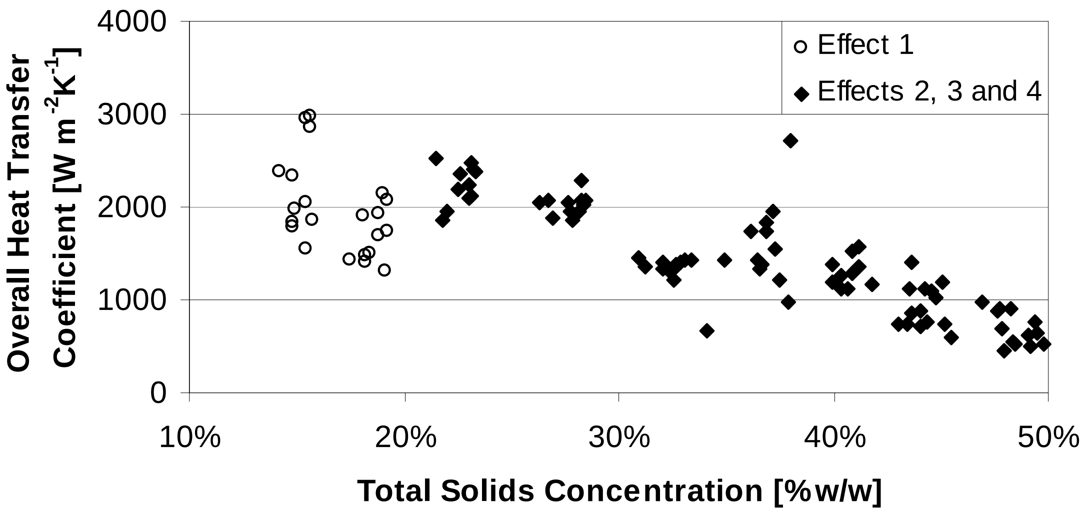


Figure 3-90: Overall heat transfer coefficients versus the outlet total solids concentrations for whole milk, from every pass of Evaporators 1 & 4.

Whole Milk OHTC Equation

An equation fitted for the OHTC of whole milk versus total solids concentration of milk from each pass. It is for milk exiting effects 2, 3 and 4 in Evaporator 1, and from data for all passes in Evaporator 4. The *TS* is the total solids of the whole milk exiting the pass. The equation is valid for milk exiting the passes from 15% to 50% total solids.

The temperature in effect 1 was approximately 68ºC, effect 2 was approximately 62ºC, effect 3 was approximately 55ºC and effect 4 was 48ºC to 50ºC.

$$U_{whole} = -5441\,TS + 3382 \qquad \textbf{(28)}$$

Improving Wetting Rates

There were concerns about the whole milk wetting rates in effects 1, 2 and 4. The following four paragraphs discuss methods to increase the wetting rates.

Complete coverage in effect 1 could be achieved by increasing the feed flowrate to the evaporators. The CD1 dryer ran approximately 10% slower on whole milk than on skim milk. Operating staff were not keen to increase the feed flowrate to the evaporators. This is because of the cyclones occasionally blocked, causing sudden dryer shutdowns while the blockage was removed.

A study of the pressure differentials in the CD2 bag-houses by John Gabites has indicated that there are less fines in the dryer exhaust air for whole milk than skim milk (2004, personal communication). One would expect that even if the throughput of whole milk was increased there would be less fines entering the cyclones than for skim milk. If already not done so, the cyclones should be investigated to find out why they block so often, with the goal of increasing throughput without blockages.

The Edendale evaporators are run at approximately 55 $m^3\ h^{-1}$ for whole milk, above a minimum of 50 $m^3\ h^{-1}$ (Steve Keelty, personal communication, 2004). The Clandeboye evaporators have the same design and ran from 40 to 47 $m^3\ h^{-1}$. Clearly, the Clandeboye evaporators have the capacity to process more whole milk.

Observations on the Wetting Rig show that once a tube is fully wet a complete film remains even at wetting rates down to half the dry tube minimum wetting rate. It is possible that the tubes were never fully wet due to the start-up procedure. A brief surge of milk at the start of the run may help fully wet the tubes in all the passes, enabling better wetting for the rest of the run.

3.4.4 MPC-85

Total Solids Profile

Figure 3-91 shows the typical total solids concentrations of MPC-85 exiting each pass in Evaporator 4 during 3-effect mode and 4-effect mode. The 3-effect mode run was sampled 5 hours after start-up and the 4-effect mode run was sampled 7 hours after start-up. The evaporators are now only operated in 3-effect mode, as this only uses one MVR fan and saves a considerable amount of energy.

Unlike skim and whole milks, MPC-85 did not have a linear concentration increase in each pass. There was little increase between passes 3 and 5 of effect 2. Foam overflowed from pass 1 into passes 2, 3 and 5 and diluted the liquid entering these passes.

Calculated Wetting Rates

Figure 3-92 shows the approximate wetting rates for underfed tubes in Evaporator 4, while it was on 3- and 4-effect modes. The minimum wetting rates are given for both heat transfer and evaporation conditions. Some liquid was lost from pass 1 of effect 2 as it overflowed to other passes as foam. As the level of overflow was always changing, this was very difficult to model.

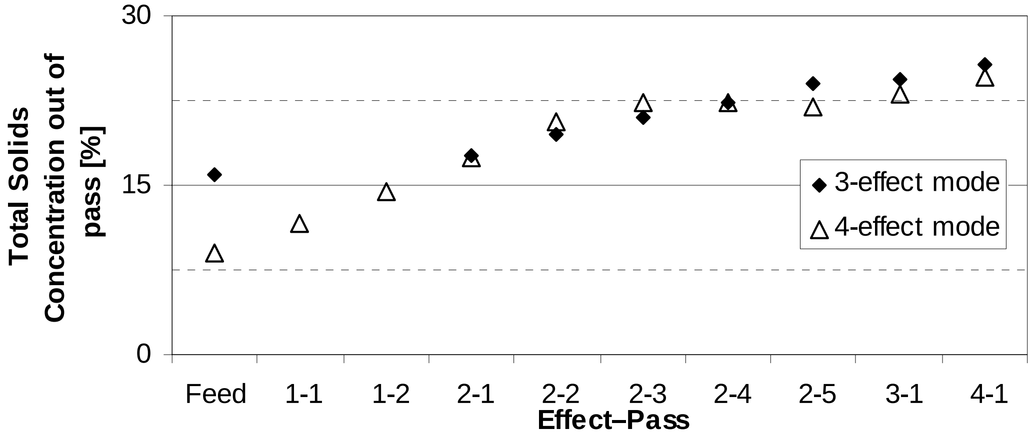


Figure 3-91: Typical total solids profiles of MPC-85 exiting each pass in Evaporator 4 while in 3-effect and 4-effect modes.

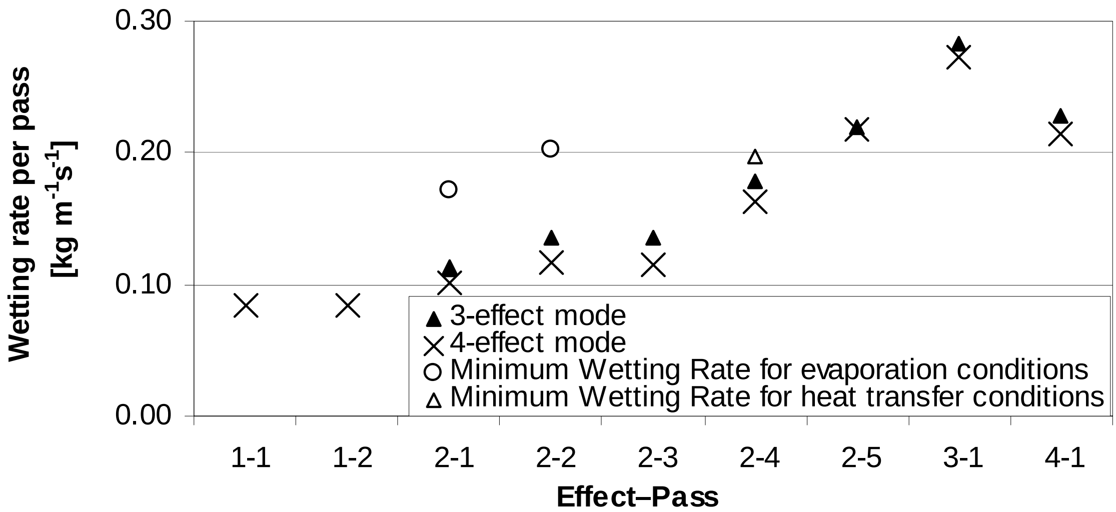


Figure 3-92: Outlet wetting rates per pass for MPC-85 in Evaporator 4 during 3-effect and 4-effect modes. Minimum wetting rates are provided for heat transfer and evaporation conditions in the wetting rig.

The actual wetting rates in passes 1, 2, 3 and 4 were lower than calculated. The foam losses from pass 1 were assumed to be minimal at the start of a run, but they become larger after about 10 hours. This was shown by a reduction in the liquid head height in passes 3 and 4 over the run. The wetting rates out of effect 2 pass 5, effect 3 and effect 4 were not affected by the overflowing.

As 4-effect operation has been discontinued, it will only be mentioned that the wetting rates in passes 1 and 2 of effect 1 were below the minimum wetting rates for heat transfer and evaporation conditions. The wetting rates were approximately 0.085 kg $m^{-1}s^{-1}$. The minimum wetting rates were 0.114 kg $m^{-1}s^{-1}$ for heat transfer conditions and 0.172 kg $m^{-1}s^{-1}$ for evaporation conditions. It is uncertain if the tubes ever completely wet.

Wetting Rates in Evaporators

The nature of MPC-85 wetting in the evaporators has been a mystery. On 5 April 2005 Evaporator 4 was opened and inspected before cleaning, having processed MPC-85 for 5 hours. The distribution plates, and the top and bottom of all the tubes were inspected in effects 2, 3 and 4.

All the tubes which were fed by three unblocked holes were clean. This shows that the wetting rates were suitable. Operator log sheets showed that the evaporator was being run similarly to Evaporator 4 on 6 May 2004. The wetting rates were assumed to be similar and estimations were made for the wetting rates of clean and fouled tubes. These wetting rates are presented in Figure 3-93.

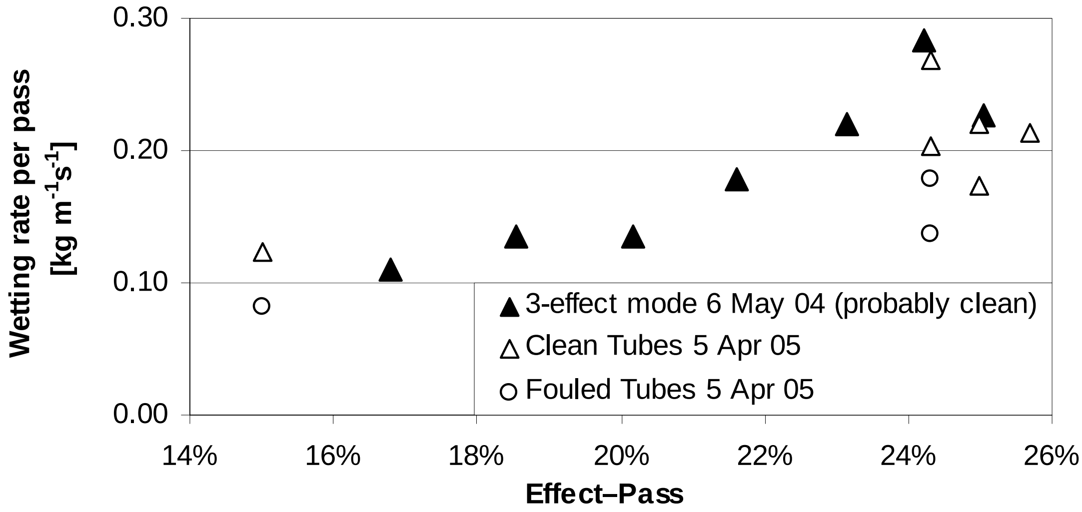


Figure 3-93: The wetting rates of MPC-85 out of each pass of Evaporator 4 on 6 May 2004, and the estimated wetting rates of clean and fouled tubes.

All OHTC Measurements

Figure 3-94 shows the calculated OHTCs in Evaporator 4 during 3-effect and 4-effect operations. There was a tremendous amount of variation in the OHTCs for MPC-85. Overflowing of foam in effect 2 caused many unexpected OHTC values. The uncertainty in the total solids concentrations gave inaccurate OHTCs out of effects 3 and 4.

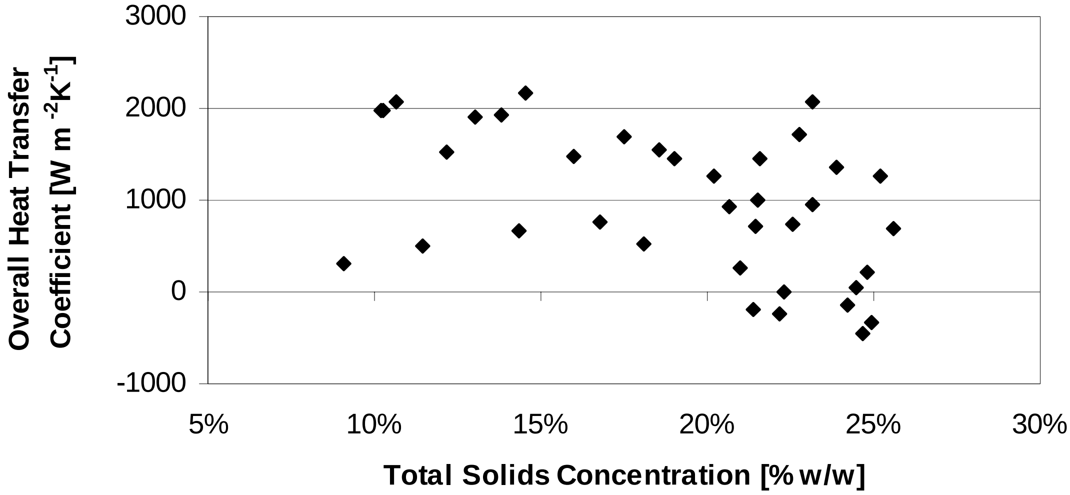


Figure 3-94: The calculated OHTCs of MPC-85 in Evaporators 3, 4 and 5 during 3-effect and 4-effect modes.

3.4.5 Conclusions

Total solids measurements from the evaporator passes gave a useful profile of the milk concentrations exiting each pass. The wetting rates in effect 4 were low for skim milk, and especially low for whole milk. The wetting rates for MPC-85 were all adequate. Correlations were developed for the overall heat transfer coefficients of skim and whole milks versus the average milk concentration in each pass.

The Edendale and Clandeboye evaporators run at very different feed flowrates, despite having nearly identical designs.

3.4.6 Sensitivity Analysis

Figure 3-95 shows that the wetting rates values had an uncertainty between 3% and 5%. This accuracy is acceptable.

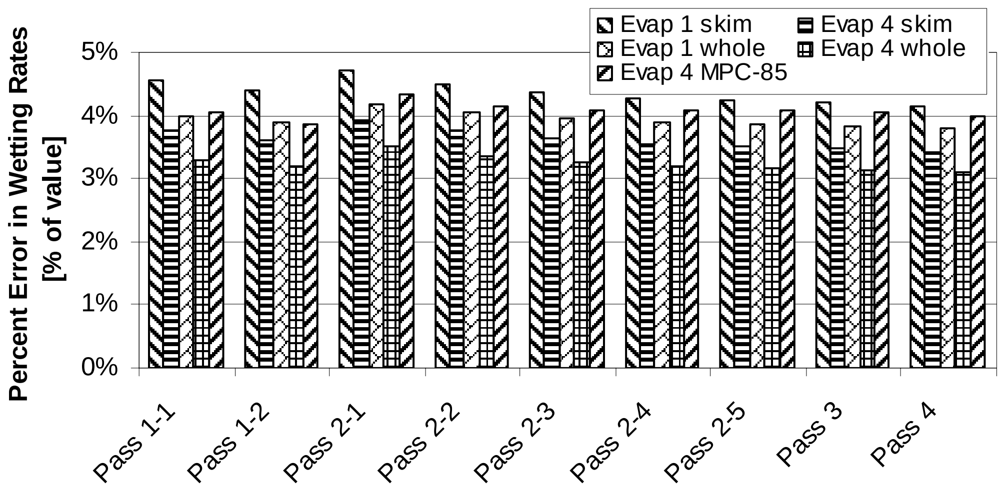


Figure 3-95: The percent error in the wetting rates, from a sensitivity analysis for Evaporators 1 and 4 processing skim and whole milks, and MPC-85.

Figure 3-96 shows the uncertainties for the OHTC values. Evaporator 1 had poorer accuracies than Evaporator 4. The cause for the high errors was significant scatter in the shell and effect temperatures, particularly in the CD1 evaporators. The temperature probes need recalibration or renewing.

The evaporation rates had excellent accuracies and are shown in Figure 3-97. The uncertainties were between approximately 2% and 4% for all the evaporators. There were high levels of uncertainty associated with flashing. As there was little flash evaporation compared to the total evaporation, flashing had little influence on the uncertainties.

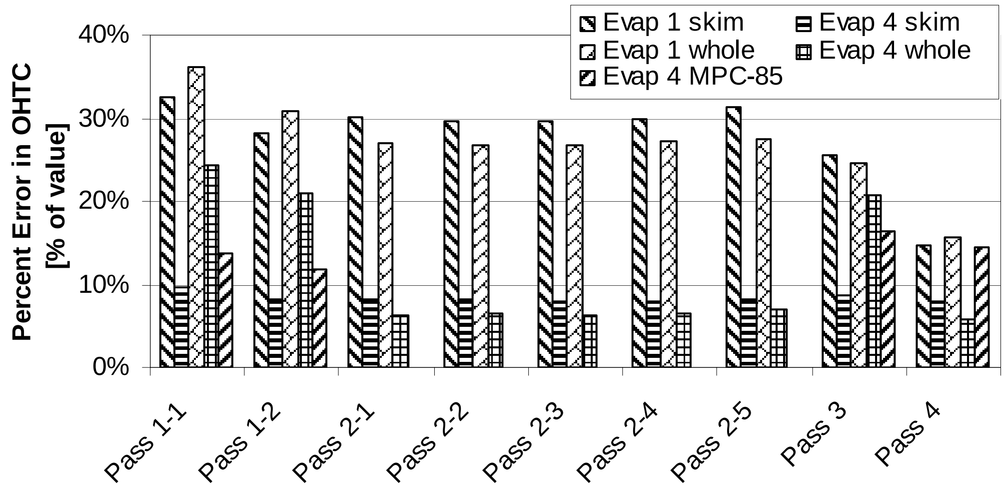


Figure 3-96: The percent error in the OHTCs, from a sensitivity analysis for Evaporators 1 and 4 processing skim and whole milks, and MPC-85.

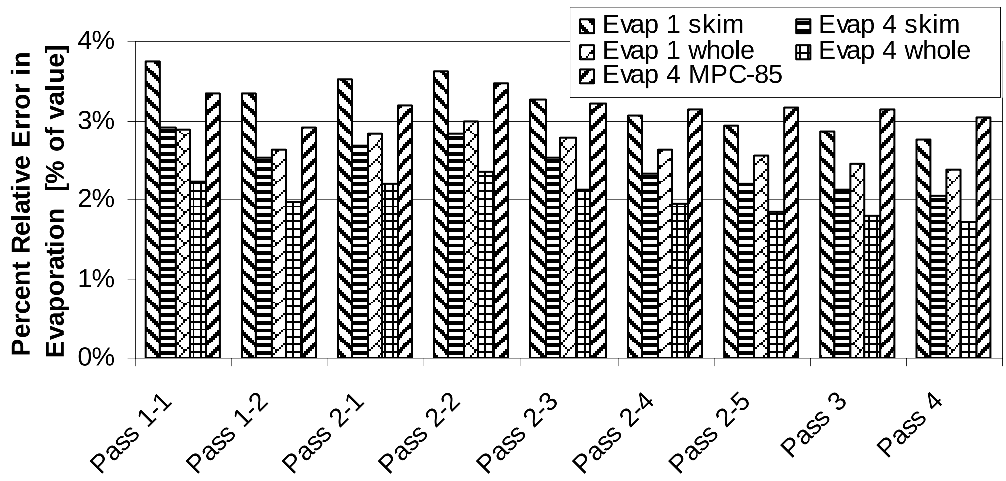


Figure 3-97: The percent error in the Evaporation rates, from a sensitivity analysis for Evaporators 1 and 4 processing skim and whole milks, and MPC-85.

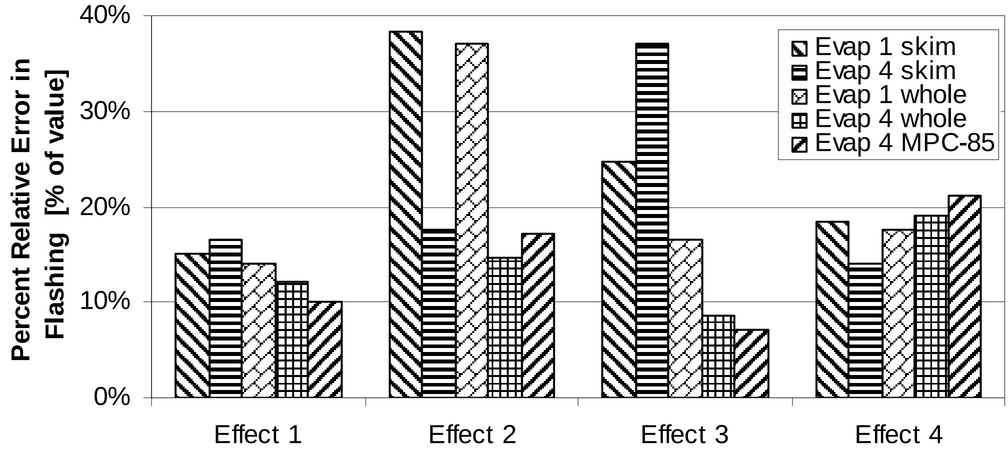


Figure 3-98: The percent error in the flashing in each effect, from a sensitivity analysis.

3.5 Upward Vapour Flows

3.5.1 Early Shutdowns

Fonterra Clandeboye experienced many early shutdowns in Evaporators 1 and 2 at the beginning of the 2003 and 2004 milk powder seasons. The shutdowns were caused because the MVR fans reached maximum speed. The skim milk at this time of the year tended to foam more easily in effect 2 than at other times of the year.

Figure 3-34 (p. 50) is repeated as Figure 3-99. It shows a skim milk run in Evaporator 2 which experienced an early shutdown because the MVR fans reached maximum speed after only eight hours. The chart displays the MVR fan speeds, the milk density out of effect 2, and the feed flowrate of skim milk.

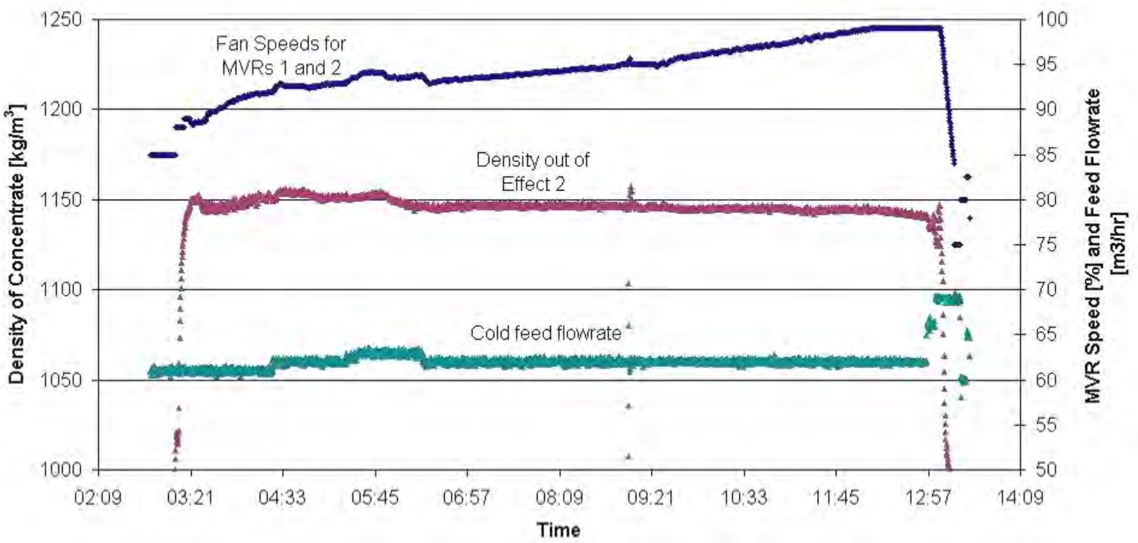


Figure 3-99: The speeds for MVR fans 1 and 2, the outlet milk density from effect 2 and the feed flowrate of cold skim milk into Evaporator 2. This was for a run which ended prematurely because the MVR fans reached maximum speed.

This was for skim milk in Evaporator 2 on 13 September 2004. It was specification 20-0126, cypher B013, which had a 77ºC DSI heat treatment for 10 seconds. This means it had a 'single-step' heat treatment.

Unfortunately, there were insufficient sample points in Evaporator 2 to take total solids measurements. Operator logbooks of the 2003-2004 milk powder season recorded approximately 30 evaporator runs which were shut down for this reason.

3.5.2 Short Run on Evaporator 1

Evaporator 1 also experienced early shutdowns. It was fortunately equipped with enough sample points. The total solids out of each pass were measured twice during such a run. The samples were taken 3 hours and 8 hours after start-up.

The MVR fan speeds increased from 91.4% to 94.3% during the run. While this was not a tremendous change in fan speed over 8 hours, the rate of increase would usually rise sharply after this point. The evaporator was shut down at nine hours for scheduling reasons, but it showed signs that it would be shut down early if it had been run for longer

The total solids samples were used to calculate the wetting rates and heat OHTCs in each pass. The next subsections discuss the results.

Total Solids Measurements

Figure 3-100 shows the total solids concentrations exiting the passes at three and eight hours.

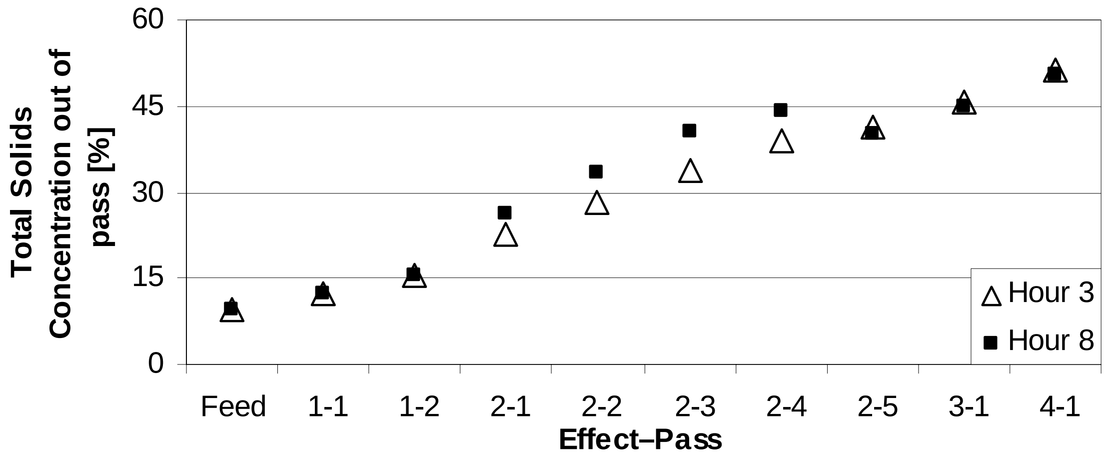


Figure 3-100: Total solids concentration out of passes in Evaporator 1 during a skim milk run in which the MVR fans were expected to approach 100% power before 18 hours.

At hour 3, the total solids were typical for a skim milk run. There was some foam in pass 1 of effect 2, but it was contained within the pass. At hour 8 there was a considerable amount of foam gushing over the distribution plate baffles from pass 1 to passes 2, 3 and 5.

There were astounding changes in the concentrations exiting the passes. The exit concentration from pass 1 changed from 23% to 26%. The concentration from pass 2 increased from 28% to 34%, from pass 3 it climbed from 34% to 41%, and pass 4 the concentration rose from 39% to 44%. The concentration out of pass 5 reduced from 41% to 40%.

These results were so unexpected that they were thought to be wrong. The laboratory procedure for total solids testing was checked. A refractometer and MilkoScan were used to cross-check the total solids concentrations. They confirmed on multiple occasions that pass 4 had very high total solids, and that dilution occurred between passes 4 and 5.

It was initially thought that seal water leaked from a pump into the product stream, diluting the product. However, the total solids results showed that the dilution only occurred at the end of runs, meaning it was dependent on run length. A pump would leak a constant amount of water into the process, irrespective of the run length.

The flow of foam out of pass 1 reduced the volume of liquid entering the pass 1 tubes. It also meant there was less liquid entering passes 2, 3 and 4. This lowered the wetting rates in these passes. The lower volume of liquid in these passes allowed over-concentration to occur.

The flowrates into pass 4 were so sometimes low there was not enough liquid to cover the distribution plate, making the holes clearly visible. The distribution plate for pass 4 was not perfectly flat and the liquid entered in pulses and formed ‘puddles.’ Some holes and tubes, especially those near the edges, did not receive liquid for long periods of time.

At hour 6 of this run the preheaters were swapped over. There was a flow disruption for 90 seconds. This gave maximum recorded flows of 70 m^3 h^{-1} and there was a minimum recorded flow of 51 m^3 h^{-1}. The typical operating flows was 63 m^3 h^{-1}. Figure 3-101 shows the recorded flows during the preheater swap. The evaporator operation changed significantly after the preheater swap.

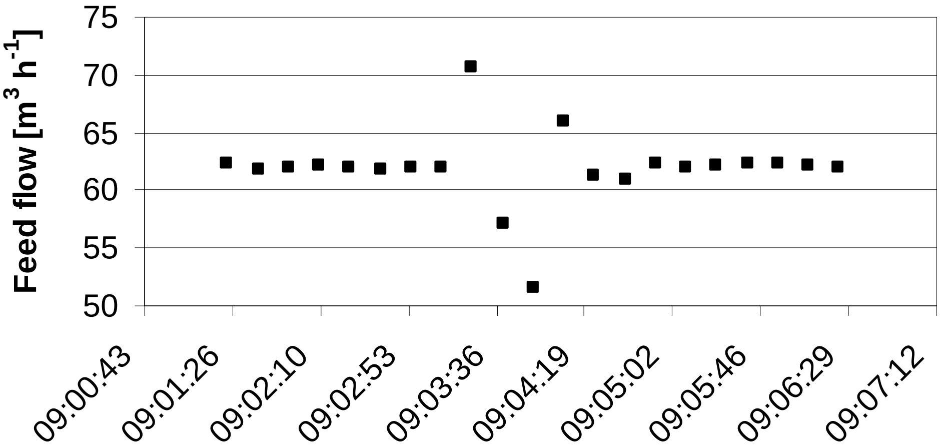


Figure 3-101: The maximum and minimum flows during a preheater swap on skim milk in Evaporator 2 on 13 September 2004.

Overall Heat Transfer Coefficients

Figure 3-102 shows the OHTC for each pass at hours 3 and 8. Most OHTCs remained constant, except for those in passes 1 and 5 of effect 2.

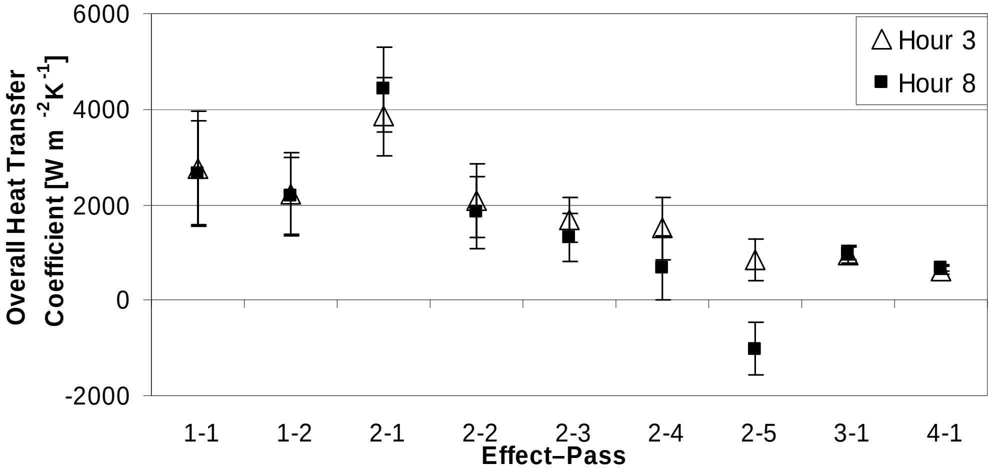


Figure 3-102: Overall heat transfer coefficient (OHTC) at hour 3 and 8 of a run for skim milk in Evaporator 1.

The OHTCs in pass 1 of effect 2 increased from 3844 to 4411 W $m^{-2}K^{-1}$. These are both unrealistically high heat transfer coefficients. In pass 5, the OHTC was 844 W $m^{-2}K^{-1}$ at hour 3. This decreased to -1016 W $m^{-2}K^{-1}$ at hour 8. The negative OHTC shows the liquid was being diluted.

The OHTCs in the other passes changed very little. The OHTC in effect 4 remained constant at approximately 650 W $m^{-2}K^{-1}$.

3.5.3 Pressure Drop Down Tubes

Calculated Pressure Drops

The pressure drops were calculated for the total solids data down the tubes in each pass. This was done for skim and whole milks only because the total solids data for MPC-85 was not suitable. Equation 25 was solved iteratively in Microsoft Excel down the tubes in 1 m intervals to find the pressure drops.

Figure 3-103 shows the calculated pressure drops down tubes in each pass of Evaporator 4. This was done for typical runs of skim and whole milks.

Skim milk had higher pressure drops than whole milk because of the higher evaporation rates. The passes in effect 2 had exceptionally varied pressure drops, which were the highest and lowest values for each milk type. The values for skim milk ranged from 320 Pa in pass 1 to 77 Pa in pass 5. The pressure drops for whole milk ranged from 148 Pa in pass 1 to 68 Pa in pass 5.

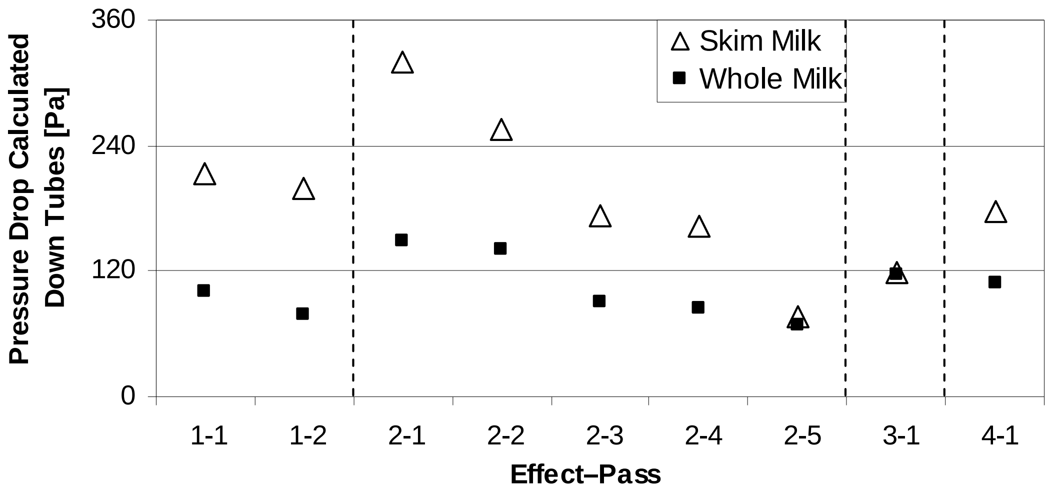


Figure 3-103: Calculated pressure drop down each pass for skim and whole milks in Evaporator 4.

The different pressure drops were caused by different evaporation rates per tube in each pass. Equation 2 is rearranged as Equations 29 and 30 to illustrate the following paragraph.

$$\dot{m}_{vap} = \frac{U\frac{\pi}{4}d_i^2\, n_{tubes}\Delta T}{\Delta h_v} \qquad \textbf{(29)}$$

$$\frac{\dot{m}_{vap}}{n_{tubes}} = \frac{U\frac{\pi}{4}d_i^2\, n_{tubes}\Delta T}{\Delta h_v} \qquad \textbf{(30)}$$

The tubes in effect 2 all had the same area and temperature difference (ΔT). This means the evaporation rate (Q) was proportional to the OHTC (U). The tubes in pass 1 had higher OHTCs than tubes in pass 5. This gave higher rates of evaporation in pass 1 and lower evaporation rates in following passes. The different evaporation rates in each pass gave the variations in the tube pressure drops.

Upward Vapour Flows

There were no partitions separating the top of the passes in effect 1 or in effect 2. This meant the overall pressure drops down each pass were equal.

The Bernoulli equation (de Nevers, 1991) was applied to the top and bottom of tubes in each pass. The pressure drops were different for tubes in each pass. A crude mass balance of the tubes showed that vapour flowed up the top of passes 1, 2 and sometimes 3. This was confirmed by observations many times. These have been termed 'upward vapour flows.' The vapour flowed up the tubes, then had to flow across the distribution section and down passes 4 and 5. The flows are illustrated in Figure 3-104.

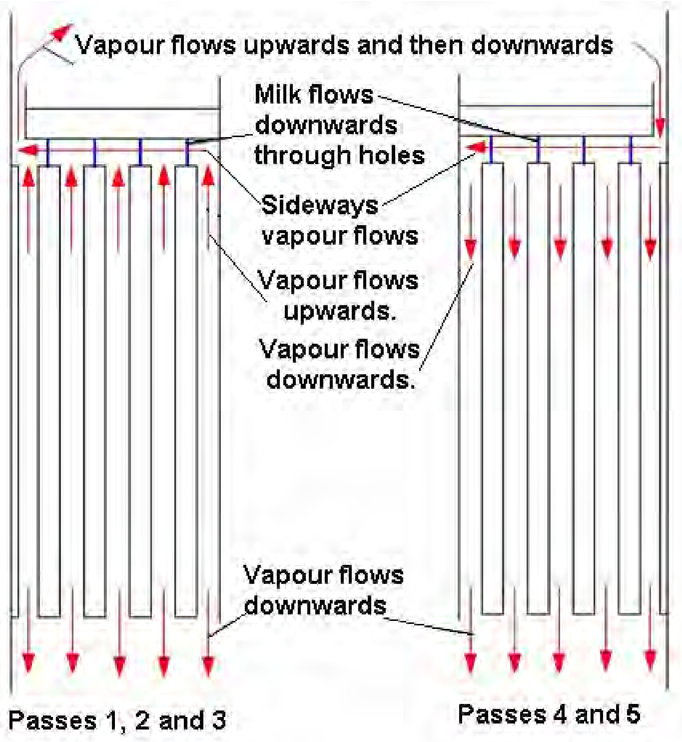


Figure 3-104: The upward vapour flows in passes 1, 2 and 3 of effect 2 and the downwards vapour flows in passes 4 and 5.

Passes 1, 2 and 3 are expected to have unusual pressure profiles. From the bottom of the tubes, the pressure is expected to rise along the length of the tubes until a point of maximum pressure. Above this height in the tube, the pressure will decrease, until it equals the operating pressure at the top of the liquid distribution section.

At the position of maximum pressure there will be zero vapour velocity. Below this position, water vapour will flow downwards. Above, the vapour will flow upwards. This means there will be counter-current flows out the top of the tubes with liquid flowing down and vapour flowing up. No literature has been found regarding upward vapour flows inside falling film evaporators.

Disruptions to Liquid Distribution

Skim milk foams easily and there is usually a considerable amount of foam in pass 1 of effect 2. This has usually been attributed to flashing. However, flashing would involve the foam forming in the basket of pass 1. On careful inspection, flashing was not the main cause of the foam. Instead, foam appeared to 'gush' up through the gap between the distribution plate and wall. It was deposited in pass 1 and built up.

Upward flowing vapour passing out of the top of the tubes would have to travel through the gap between the tubesheet and distribution plate. This gap was 40 mm high and the total cross sectional areas of the gaps in each pass were significantly smaller than the cross sectional areas of the tubes. Figure 3-105 shows the cross sectional area of tubes in each pass and the size of the gap between the distribution plate and the tubesheet.

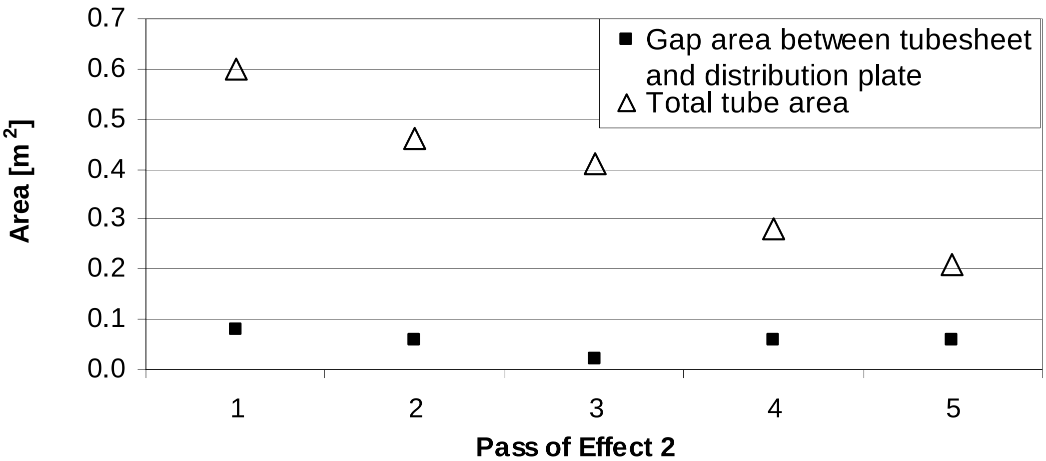


Figure 3-105: The total area of the tube cross sections, and the area of the gap between the distribution plates and tubesheet, for each pass in effect 2.

The upward-moving vapour must hit the distribution plate and then change direction to move sideways, moving to the edge of the tubesheet. As the vapour travelled sideways, the mass flows from the tubes would have combined. This accumulation would have increased the mass flowrates and the vapour velocities. (Meanwhile, rivulets of milk would still fall from the distribution plate to the tubesheet.)

Foaming

The conditions between the tubesheet and distribution plate can only be speculated, but it is likely that the conditions are particularly turbulent, with high-speed contact between the liquid and vapour. This is the likely cause of the foam in pass 1.

Excess foam in pass 1 was expected to overflow down the gap between the distribution plate and the wall. This could not happen because vapour and foam travelled up through the gap. The baffles separating pass 1 from the other passes were 400 mm high while the baffles dividing the other passes were only 300 mm high. This almost suggests that there were foaming problems in previous evaporator designs and that the baffle height was raised to contain the foam. Sometimes the level of foam in pass 1 was so high that despite the 400 mm baffles, foam still overflowed to passes 2, 3 and 5. This is illustrated in Figure 3-106.

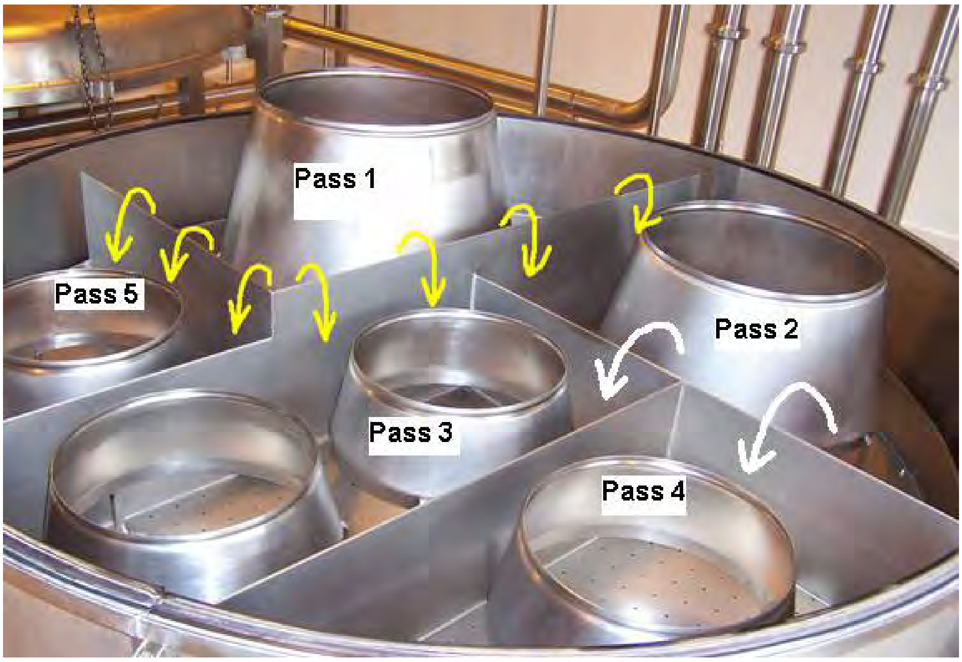


Figure 3-106: Foam overflowing from pass 1 to passes 2, 3 and 5. In extreme cases foam overflowed from pass 2 to passes 3 and 4.

In exceptional cases, which included some start-ups, the foam was so high that it totally covered the distribution plate. This increased the time taken to reach steady operation.

Good operation includes having no foam overflowing between passes. Raising the heights of the baffles for pass 1 is a logical response to contain the foam but is not recommended. This could allow the level of the foam to frequently be above the pass 1 spray plates. This occasionally happened with foaming skim milks. Flash vapours built up inside the basket and sent jets of foam in all directions. Increasing the baffle height would make this happen more often.

Flows Around and Under the Distribution Plate

Some vapour flowed around the distribution plate, rather than over it. Pass 5 is next to pass 1 and a ‘raging river’ of foam was usually seen flowing from pass 1 to pass 5 in the gap between the distribution plate and the wall. This is illustrated in Figure 3-107.

The warping of the distribution plates created gaps between the tubesheet partitions and the distribution plate. In Evaporators 1 and 2 there are large vertical gaps between the partition of passes 1 and 5 and the distribution plate. Vapour and entrained liquid were expected to flow through these gaps. These flows are also shown in Figure 3-107.

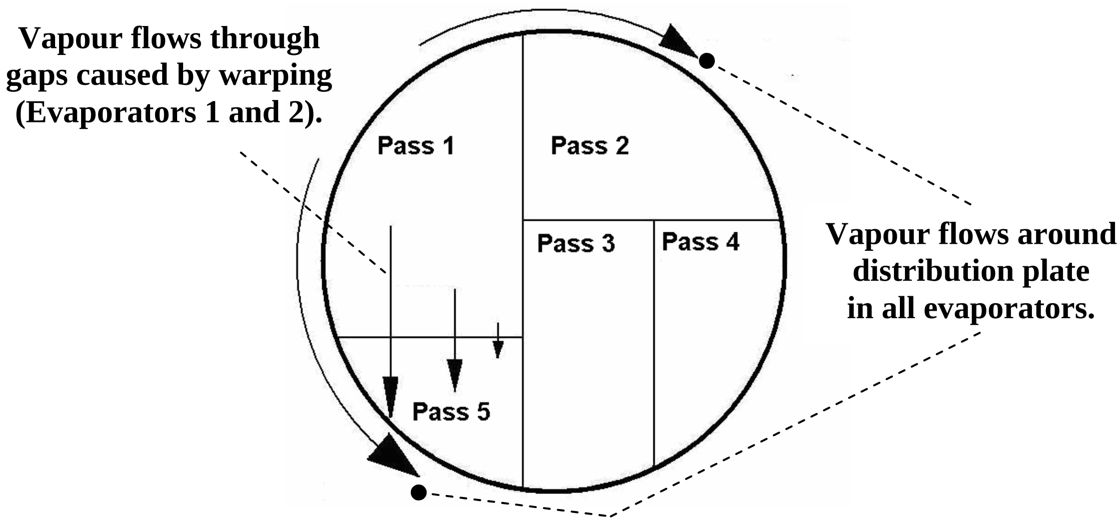


Figure 3-107: The vapour flows around and under the distribution plates in effect 2 of the evaporators.

Installing a vertical baffle in the vapour gap between passes 1 and 5 has been suggested. This would disentrain the liquid foam from the ‘raging river’ of vapour but it could be difficult to clean.

3.5.4 Conclusions

Some preheater swaps caused feed flowrate disruptions which lowered the feed flowrates to 50 m^3 h^{-1}. The average feed flowrate of 63 m^3 h^{-1}. This appeared to affect the performance of the evaporators and may have contributed to early shutdowns.

Early shutdowns of the evaporators were a problem and high levels of foaming were observed in effect 2 during such runs. Effect 2 processed milk from approximately 20% to 40% total solids. These milks had different OHTCs which caused the evaporation rates per tube to be different. This gave different pressure drops down each tube in each pass.

The top and bottom of the passes were at constant pressure. Observations and calculations have shown that vapour flowed up passes 1 and 2, across the distribution section and down passes 4 and 5.

This disturbed the distribution of milk onto the tubesheet and deposited foam in pass 1. Sometimes this foam overflowed across the distribution plate into passes 2, 3 and 5. Total solids measurements with skim milk and MPCs have shown that this significantly diluted the milk. This dilution of the milk increased with the length of the run.

4. Design Modifications and Recommendations

4.1 Overview

This section details the proposed modifications for effects 2 and 4. The structure as follows:

4.2 Goals of Modifications.

4.3 Design changes for effect 4 in existing evaporators.

4.4 Design changes for effect 4 in future evaporators.

4.5 Information used for effect 4 design modifications.

4.6 Low cost modifications to effect 2 in existing evaporators.

4.7 Higher cost retrofitting for effect 2 in existing evaporators.

4.8 Designs for effect 2 in future evaporators.

4.9 Costs and benefits of modifications on operations.

4.10 Approximate costs of modifications.

4.2 Goals of Modifications

The goal of the modifications was to improve liquid distribution, reducing fouling and associated thermophilic growth rates. The build-up of fouling consumed a considerable amount of cleaning time, utilities and chemicals. Usually only a small fraction of tubes were fouled and the entire evaporator had to be cleaned until all the fouling is removed. Correcting the effect 2 and 4 distribution system designs will:

- Reduce fouling.
- Reduce thermophilic bacteria growth in the evaporators.
- Lower product contamination by bacteria.
- Give longer run lengths.
- Reduce the frequency and length of cleans and evaporator downtime.
- Reduce the amount of chemicals and utilities used in cleaning.

4.3 Design changes for effect 4 in existing evaporators

The number of tubes in effect 4 will be reduced from 96 to 80 to increase the outlet wetting rate. The distribution plate will be redesigned to give a uniform liquid distribution.

Figure 4-108 shows the tubesheet in effect 4 with 80 tubes and the configuration of holes around the tubes. The holes were sized according to the number of tubes they fed. The 16 blocked tubes were erased from the picture.

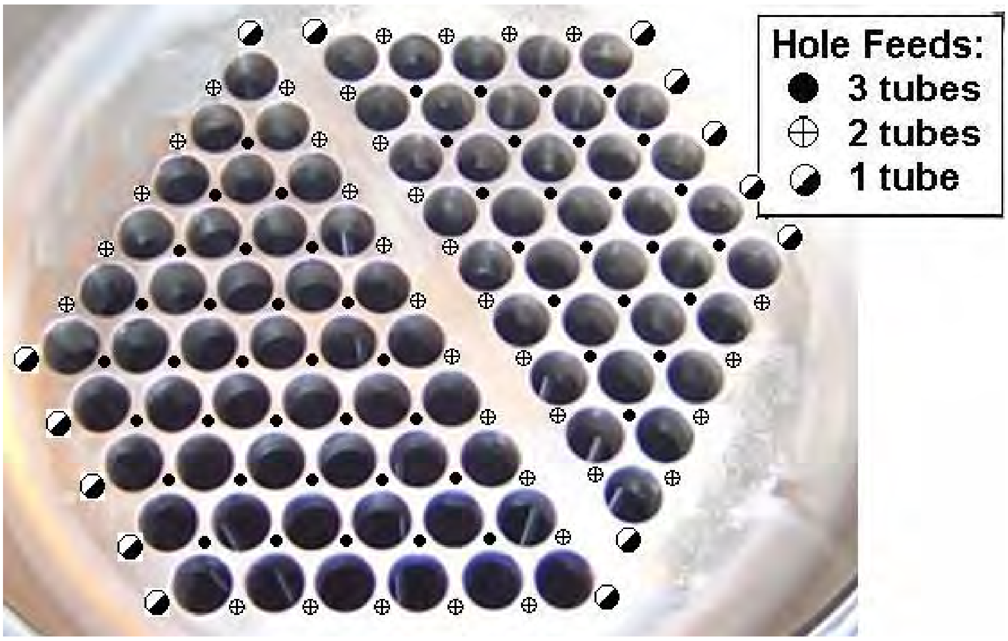


Figure 4-108: The new configuration of effect 4 with 80 tubes. The 16 blocked tubes have been erased.

The positions of the distribution plate holes will not change. The modifications involve totally blocking some holes, enlarging the size of holes feeding three tubes and reducing the size of holes feeding one or two tubes.

It is cheaper to modify the existing distribution plate than to fabricate a new distribution plate. There was minimal warping of the effect 4 distribution plates.

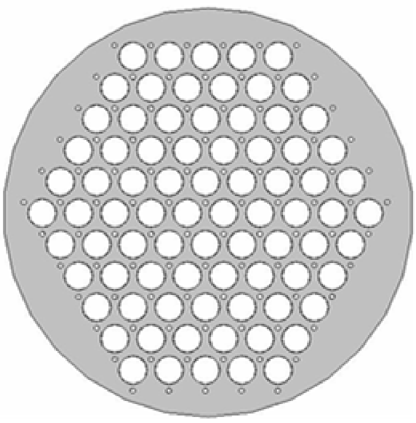
As there were no fouling problems with effect 3, the tubesheet and distribution plate do not need to be modified, even though there was a significant liquid misdistribution.

The heights of the deflector baskets were inconsistent through the Clandeboye evaporators. Most baskets were too low. The bottom of the open basket must be above the height of the edge of the distribution plate. This allows foam to overflow across the edge of the plate. Foam built up in the basket and squirted in pulses out the top of the basket.

4.4 Designs for effect 4 in future evaporators

Future designs of effect 4 should have 80 tubes with no tube-split. Figure 3-39 (p. 82) shows the fouling that forms on the underside of the effect 4 tubesplit. A single-pass tubesheet would eliminate this fouling and make the design of an effective distribution plate much simpler. The effect 3 and 4 tubesheets would both have 80 tubes and should have identical designs.

The distribution plates should have the same hole layout but there would be smaller holes in effect 4 because of the lower milk flowrates. The holes should be correctly sized and drilled to give a uniform liquid distribution. Figure 4-109 and Figure 4-110 show the proposed designs of the tubesheets for effects 3 and 4, and the placement of holes around the tubes.



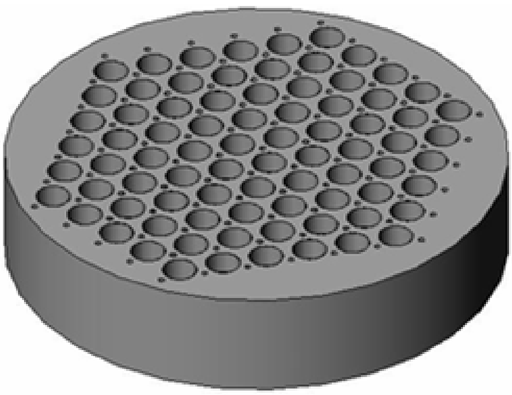


Figure 4-109 **Figure 4-110**

Design of the tubesheet for effects 3 and 4 with the configuration of holes around these tubes. The holes must be sized according to the number of tubes they feed.

4.5 Information used for effect 4 design recommendations

The outlet wetting rates in effect 4 for each milk type, the vapour velocities and the associated pressure and temperature drops down tubes were used to determine the best number of tubes in effect 4.

4.5.1 Outlet wetting rates

The average wetting rates for skim milk, whole milk and MPC-85 out of effect 4 were calculated for Evaporators 1 to 5 over all the measured runs. Figure 4-111 shows the average wetting rates in the underfed tubes and also shows the expected wetting rates if there were perfect liquid distributions with 96 and 80 tubes. Minimum wetting rates are provided for the milk concentrates under heat transfer and evaporation conditions.

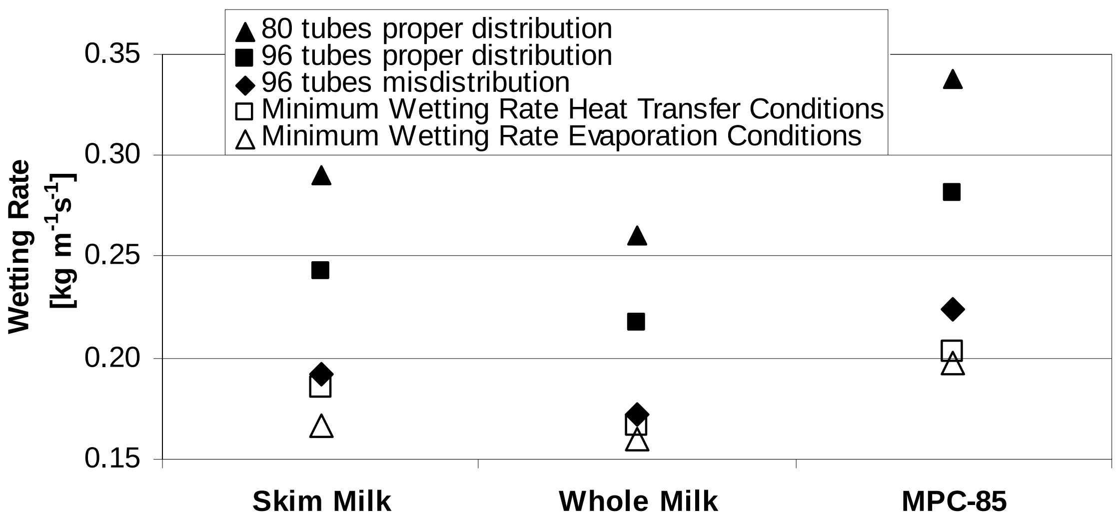


Figure 4-111: Typical wetting rates out of effect 4 for skim and whole milks, and MPC-85. This is for the current misdistribution with 96 tubes and for perfect distributions with 96 and 80 tubes.

This shows that having a perfect liquid distribution with 96 or 80 tubes gives acceptable wetting rates. 80 tubes will be used because there were a large number of flow disruptions in the evaporators, especially during preheater swaps which caused low flowrates for short periods of time. The increased wetting rates will help reduce film breakup during these disruptions.

The following subsections show the wetting rates in all the passes for each milk type.

Skim Milk

Figure 4-112 shows the outlet wetting rates for skim milk in effect 4 with the proposed modifications. It is displayed alongside the wetting rates from the other passes. The wetting rates are shown for Evaporators 1 and 4.

The minimum wetting rate for 40% skim milk under evaporation conditions is 0.186 kg $m^{-1}s^{-1}$. The average outlet wetting rates were between 0.184 and 0.201 kg $m^{-1}s^{-1}$. A perfect liquid distribution would give an outlet wetting rate of 0.242 kg $m^{-1}s^{-1}$ and using 80 tubes would give a wetting rate of approximately 0.291 kg $m^{-1}s^{-1}$. The wetting rates would be well above the minimums.

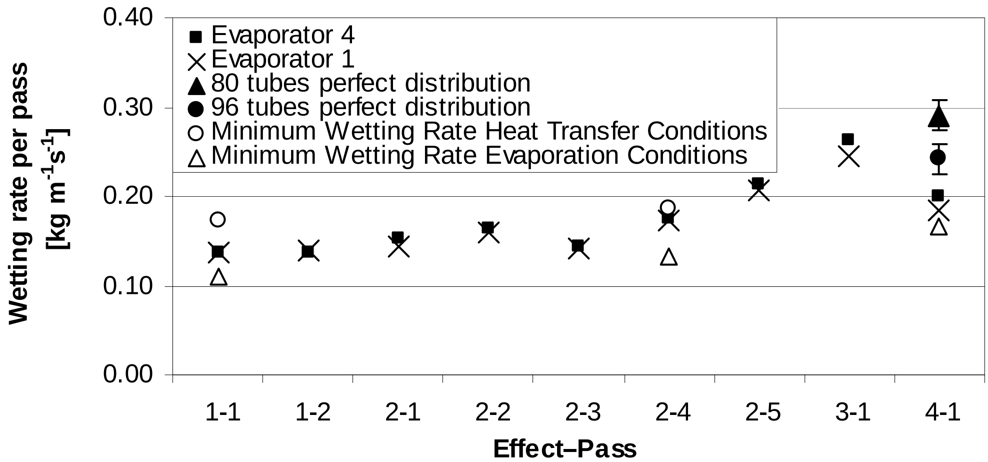


Figure 4-112: Outlet wetting rates in all passes for skim milk. The effect 4 wetting rates are for the current distributor and for perfect distributions with 96 and 80 tubes. The minimum wetting rates are provided for heat transfer and evaporation conditions.

Whole Milk

Figure 4-113 shows the outlet wetting rates for whole milk exiting all passes of Evaporators 1 and 4. Whole milk had the lowest wetting rates because the evaporators and dryer were run very conservatively. The wetting rate out of effect 4 would be more acceptable with 80 tubes than 96 tubes. Process disturbances such as preheater swaps sometimes caused low flows and the higher wetting rates would reduce films breaking.

Having 80 tubes would give outlet wetting rates of approximately 0.260 kg $m^{-1}s^{-1}$ for Evaporators 1 and 4. These values would be higher than the minimum wetting rate of 0.167 kg $m^{-1}s^{-1}$ for 40% whole milk under evaporation conditions. It would be significantly higher than the approximate wetting rate of 0.18 kg $m^{-1}s^{-1}$ which was observed for 50% whole milk in the evaporator tubes on 26 May 2004.

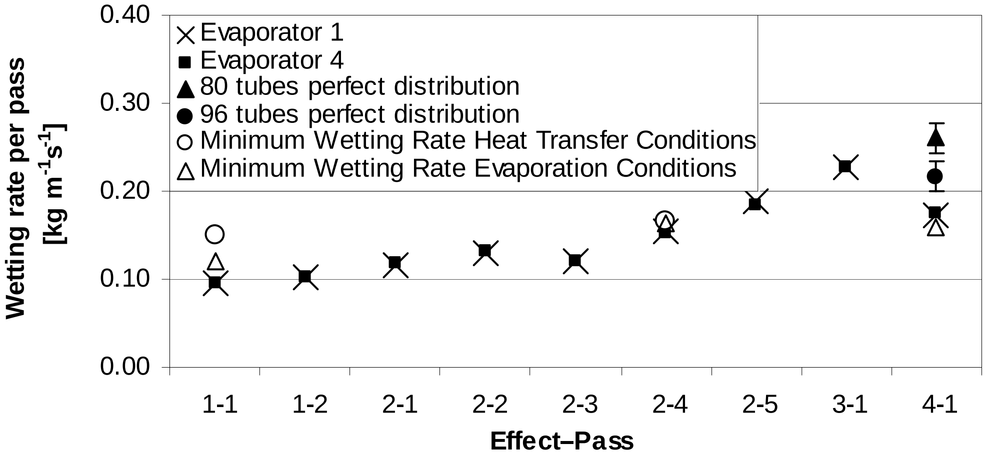


Figure 4-113: Outlet wetting rates in all passes for whole milk. The effect 4 wetting rates are for the current distributor and for perfect distributions with 96 and 80 tubes. The minimum wetting rates are provided for heat transfer and evaporation conditions.

MPC-85

Figure 4-114 summarises the wetting rates in all passes for MPC-85 in Evaporator 4. There were no wetting concerns for MPC-85 because the tubes were observed as clean in Evaporator 4 on 5 April 2005 when there had been an approximate outlet wetting rate of 0.214 kg $m^{-1}s^{-1}$. The outet wetting rate for 80 tubes would increase to 0.338 kg $m^{-1}s^{-1}$.

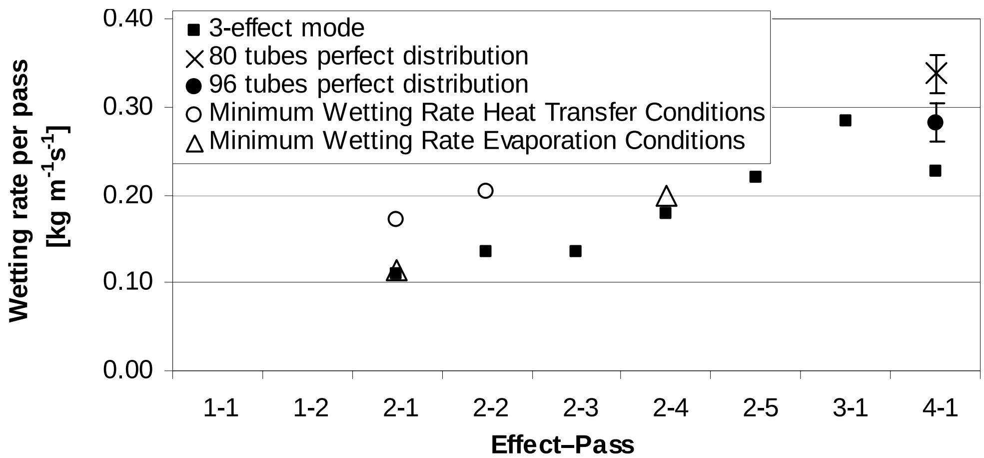


Figure 4-114: Outlet wetting rates for all passes for MPC-85 in Evaporator 4. The effect 4 wetting rates are for the current distributor and perfect distributions with 96 and 80 tubes. The minimum wetting rates are provided for heat transfer and evaporation conditions.

4.5.2 Outlet vapour velocity

Decreasing the number of tubes while maintaining the same amount of evaporation would increase the vapour velocity. The typical outlet vapour velocities were calculated for 96 and 80 tubes and are shown in Figure 4-115. These were for skim and whole milks and MPC-85 in Evaporator 4. The uncertainties were ± 12 m s^{-1} for skim milk, ± 14 m s^{-1} for whole milk and ± 8 m s^{-1} for MPC-85.

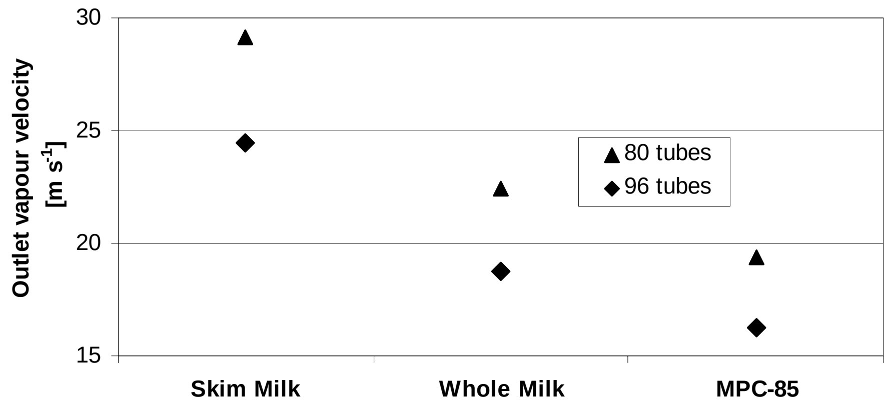


Figure 4-115: Typical vapour velocities out of tubes in effect 4 for 96 and 80 tubes for skim milk, whole milk and MPC-85.

4.5.3 Tube length temperature drop

The increased vapour velocity would give a larger pressure drop and associated temperature drop down tubes. This would decrease the shell-to-effect temperature difference. Figure 4-116 shows the expected temperature drop for 80 and 96 tubes. The temperature drop would only rise from 0.30ºC to 0.40ºC if the number of tubes was reduced from 96 to 80.

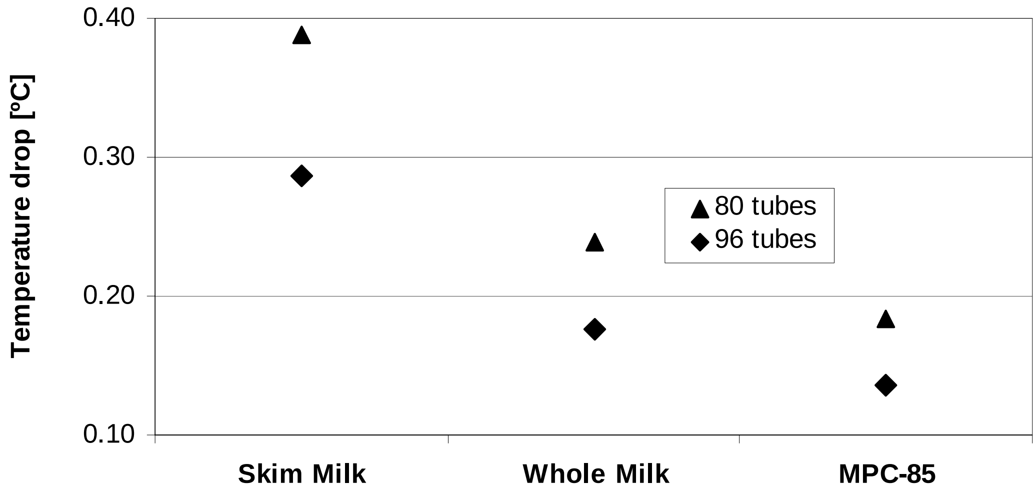


Figure 4-116: Typical temperature drop along the length of the effect 4 tubes due to the increased vapour velocity.

4.6 Low cost modifications to effect 2 in existing evaporators

4.6.1 Overview

This section discusses two possible methods of modifying the design of effect 2. The problems with the existing designs are as follows:

- Lack of partitions dividing the top of the passes from each other.
- Warped distribution plates.
- Lack of a filter between 3-effect DSI and effect 2 for MPC production.

The lack of partitions caused upward vapour flows which created and deposited large amounts of foam in pass 1. The warped distribution plates allowed vapour to carry entrained liquid from pass 1 to pass 5 underneath the distribution plates. The lack of a filter between the DSI and effect 2 during 3-effect MPC operation allowed burnt chunks to block distribution plate holes, causing fouling in the underlying tubes. One filter is required after the MPC DSI on Evaporators 3 and 4.

4.6.3 Design changes

This solution involves making novel design alterations to the existing effect 2 distribution plates. The modifications would be as follows:

    - Changing the heights of the dividers between the passes on the distribution plate to encourage any excess foam to flow to pass 2 rather than passes 3 or 5.
    - Installing vapour risers throughout the distribution plate for the release of upward-flowing vapour.
- Raising the height of the partitions in the effect 2 tubesheet so that there are no gaps between the distribution plate and tubesheet.

This design is intended to reduce the amount of foam being deposited in pass 1, and ensure any overflowing foam goes only to pass 2. it does not stop the upward vapour flows from occurring. It involves substantially less work than retrofitting the liquid distribution section with new distribution plates.

Divider heights

Figure 4-117 shows that the current divider heights are 300 mm between all passes except for those in pass 1 which are 400 mm high. Figure 4-118 displays changes in the heights of the dividers. This will encourage foam to overflow from pass 1 to pass 2, rather than pass 5. Any excessive foam would flow from pass 2 to 3, and then to pass 4.

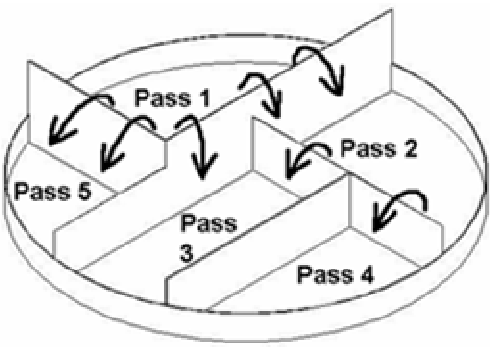


Figure 4-117: The current effect 2 distribution plate, and the overflow of foam when processing skim milk and MPCs.

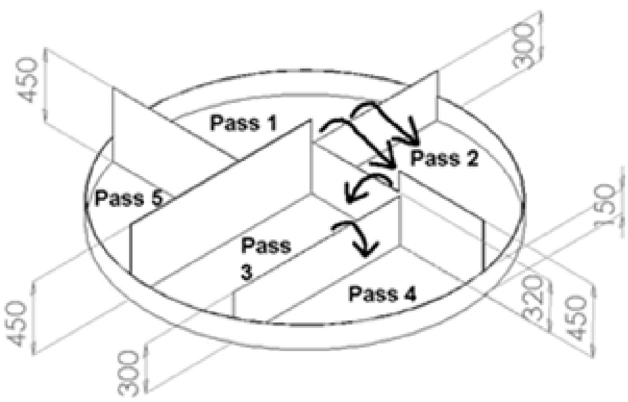


Figure 4-118: Modifications to the baffle heights of effect 2. This will make foam overflow preferentially from pass 1 to pass 2. Surplus foam will overflow to passes 3 and 4.

Vapour Risers

Vapour risers should be installed evenly across the distribution plates so that vapour can travel up through the distribution plate, rather than sideways through the small gap between the tubesheet and distribution plate. They should be made higher than the maximum liquid head height and should not be placed inside the basket. Further work is required to determine their diameter, number and geometric layout.

Warping

Communications between Dr. Ken Morison and Dr. John Smaill, a senior lecturer in mechanical engineering at the University of Canterbury, indicated that it would be extremely difficult to bend the warped distribution plates back into shape.

Raising the heights of the partitions on the tubesheet would block the gaps through which vapour and milk travel. This is shown in Figure 4-119. However, there would still be a large variation in the liquid head height of passes 1 and 5 in Evaporators 1 and 2. Figure 3-46 shows that passes 1 and 5 are level but non-horizontal. It may be possible to cut passes 1 and 5 off the distribution plate and welding them on horizontally.

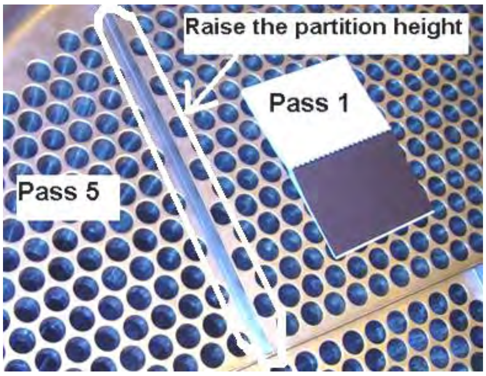


Figure 4-119: The heights of the tubesheet partitions in Evaporators 1, 2 and 4 could be raised to block gaps caused by warped distribution plates.

As a last alternative new distribution plates could be fabricated. This would be expensive.

4.7 Higher cost retrofitting of effect 2 in existing evaporators

This solution involves modifying the entire liquid distribution section in effect 2. This would be a large task. The likely changes are as follows:

- Installing metal partitions in the lid of effects 1 and 2 which reach down to the tubesheet.
- Changing the distribution plate designs.

Figure 4-120 shows a possible design which has metal partitions dividing the top of the passes. This is based on the Stork evaporator lid design in Edendale's Evaporator 2 which is shown in Figure 4-121. The partitions would be attached to the lid, and touch the tubesheet, providing a physical seal between the top of the passes. This will stop upward vapour flows occurring, and prevent any liquid flowing between the passes.

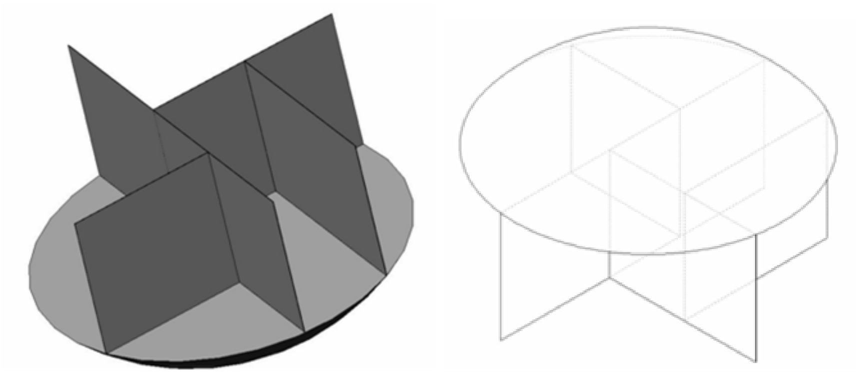


Figure 4-120: Metal partitions for the effect 2 calandria lid, forming a seal between passes when resting on the tubesheet.

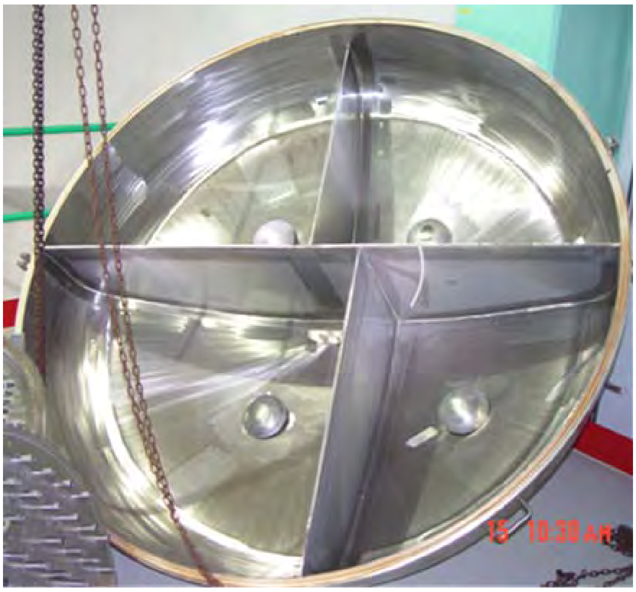


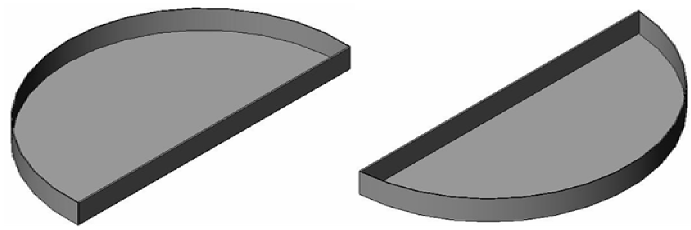
Figure 4-121: The Stork calandria lid for Edendale's Evaporator 2.

There are two options for the distribution plate design. The evaporator could be retrofitted with a Stork evaporator design, where a flat distribution plate is 'sandwiched' between the lid and tubesheet, and vapour risers are placed above every tube. Alternatively, the basket and spray plate design could be retained.

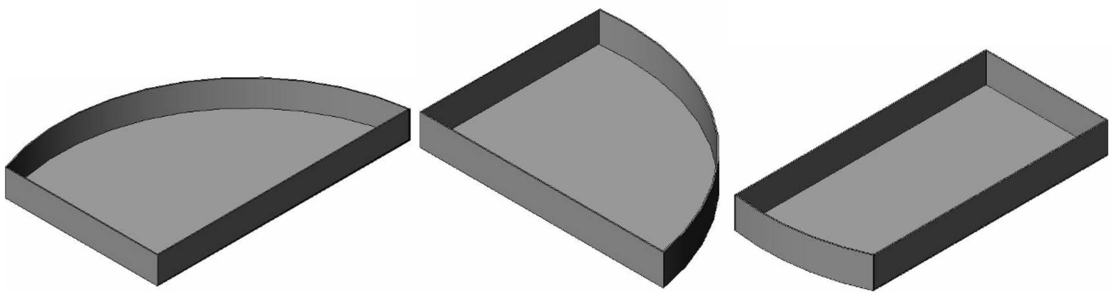
The simplest solution would be to cut the unwarped existing distribution plates into individual plates and fit them separately into each pass. These plates should have a vapour gap around them for any flash vapours and have a 150 mm maximum liquid head height, similar to the existing design. There would be no need for vapour risers because the metal partitions would prevent upward vapour flows and flash vapours should be minimal.

There should be two viewing ports installed for each pass. One port would be for shining a torch inside and the other for viewing the inside of the distribution section.

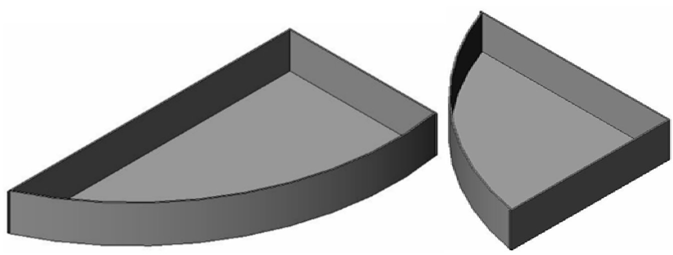
Figure 4-122 shows what the individual plates could look like for effects 1 and 2 if they were installed as individual distribution plates.



Effect 1: Pass 1 Pass 2



Effect 2: Pass 1 Pass 2 Pass 3



Pass 4 Pass 5

Figure 4-122: The individual distribution plates for passes 1 and 2 of effect 1, and in passes 1 to 5 of effect 2. The recommended edge height is 150 mm.

4.8 Designs for effect 2 in future evaporators

Future evaporators should be built differently to the current design. Partitions must physically separate the tops of the passes from each other to prevent upward vapour flows. This will stop foam forming and building up in pass 1. It will reduce the time taken for evaporators to reach steady operation and improve evaporator control. Effects 1 and 2 should have individual distribution plates and two viewing ports in each pass. The spray plate and basket design should be retained. There should be more holes drilled in the spray plates with 15 mm spacing to decrease fouling. Evaporators with MPC processing capabilities must have filters installed after the DSI.

4.9 Costs and benefits of modifications on operations

4.9.1 Current costs

An evaporator clean had an approximate chemical and utility cost of NZ$700 and there were approximate milk losses of NZ$200 per run (James Winchester, personal communication, 2005). The 1287 cleans in the 2003-2004 season cost approximately NZ$1,158,000. The 35 blocked tubes in the 2003-2004 season cost approximately NZ$52,500 to unblock (Chris Johnson, personal communication, 2005). This makes the total costs due to fouling in evaporators approximately NZ$1,210,000.

4.9.2 Benefits

The modifications to the evaporators should allow the evaporators to run longer. Increasing the average run length from 15 to 20 hours would reduce cleans by 33%, saving up to NZ$386,000 in cleaning costs and milk losses. This gives potential annual savings of up to NZ$436,000.

4.10 Approximate costs of modifications

4.10.1 Effect 4

The cost for modifications to effect 4 for Evaporators 1 to 5 are expected to total approximately NZ$15,000. (James Winchester, personal communication, 2005.)

4.10.2 Effect 4

Retrofitting effect 2 of Evaporators 1 to 5 would cost a total of approximately NZ$150,000. (James Winchester, personal communication, 2005.) The low cost modifications will cost less.

5. Conclusions

The minimum wetting rates of reconstituted whole milk, unstandardised skim milk and milk protein concentrate with 85% protein content (MPC-85) were measured in a model evaporator tube. This was for dilute and concentrated milks at 60ºC under isothermal, heat transfer and evaporation conditions. The evaporation minimum wetting rates were between 0.10 kg $m^{-1}s^{-1}$ and 0.20 kg $m^{-1}s^{-1}$ and were higher than under heat transfer or isothermal conditions.

Total solids measurements of milk exiting each pass of Clandeboye's evaporators were taken for skim milk, whole milk and MPC-85. Correlations were developed for the overall heat transfer coefficients versus the average concentrations in each pass.

The wetting rates in each pass were calculated from the total solids data. The wetting rates in effect 4 were low for skim and whole milks, but were acceptable for MPC-85.

Physical measurements of the distribution systems in each pass of every evaporator showed that there were inadequate quality checking procedures by Niro and Fonterra. Some holes were incorrectly sized and some distribution plates were warped.

An analysis of the arrangements of tubes and distribution plate holes predicted an uneven liquid distribution. The tubes in effects 3 and 4 were split into two apparent passes although both effects operated as single pass units. This gave large predicted misdistributions with half the tubes receiving less than the average flow of liquid. The method for calculating wetting rates in tubes has been revised.

A cold water trial for effects 3 and 4 confirmed that liquid was distributed poorly. Distribution plates constructed from acrylic with carefully calculated hole sizes had better liquid distributions than Niro's distribution plates.

Effect 4 of Evaporators 1 and 2 was opened after 22 hours of continuous whole milk production but before cleaning. The approximate minimum wetting rate was estimated to be 0.18 kg $m^{-1}s^{-1}$ for 50% whole milk. After five hours of MPC-85 production burnt chunks from the MPC DSI blocked many distribution plate holes in effect 2, causing numerous tubes to foul. Installing a filter after the DSI would stop the chunks entering the process, thus reducing fouling and cleaning chemical usage.

The calculated tube pressure drops were different for each pass. This was because the overall heat transfer coefficients and tube evaporation rates lowered as the total solids increased. The top of the passes in effect 2 were at a common pressure, allowing vapour to flow up the top of passes 1, 2 and 3 and down passes 4 and 5. Entrained foam was deposited in pass 1 for skim milks and MPCs. This contributed to the MVR fans reaching maximum speed prematurely, forcing the evaporator to shut down early.

The fouling in effect 4 was caused by incorrect hole sizing, poor distribution plate design and high tube surface area. This caused some tubes to foul and block. Sixteen tubes in effect 4 will be welded shut to reduce the surface area. The distribution plate will be redesigned to give a uniform liquid distribution. This will reduce fouling.

It cost approximately NZ $30,000 to unblock tubes in effect 4 in the 2003-2004 milk powder season. Effect 4 modifications will cost a total of approximately NZ $15,000.

The recommended alteration to effect 2 is to install vapour risers in the distribution plates. This will divert the upward-flowing vapour so that there will be less foam deposited in pass 1. The heights of the dividers between the passes should be modified to divert overflowing foam to pass 2, rather than other passes. Gaps caused by warped distribution plates should be filled and if possible, plates straightened.

Installing a filter, installing vapour risers and changing the partition heights would significantly improve distribution and reduce fouling. Retrofitting the distribution section of effect 2 would be very expensive, with little additional benefits.

The changes to effects 2 and 4 are expected to reduce fouling and the growth of thermophilic bacteria in the product. This will allow the evaporators to run for longer. Increasing the run lengths from the current average of 15 hours to 20 hours could reduce cleans by 33%, amounting to potential savings of NZ $438,000.

Future evaporators should be designed with single pass tubesheets in effects 3 and 4. The distribution plate design must be improved to give an even liquid distribution to the tubes. Effect 2 should be designed to prevent vapour flowing upwards. This would be done by physically dividing the top of the passes from each other. There must be better measures to prevent the distribution plates warping, and filters must be installed after all DSI units.

6. Further Works

It would be beneficial to research the following aspects of the evaporators:

- The improvements in production due to modifying the distribution plates.
- A computational fluid dynamics analysis of the distribution plates. Nathan Bushnell at the University of Canterbury is currently doing this as a part of a PhD project.
- Establishing best practices for designing evaporator distribution systems.
- Investigating the onset of nucleate boiling.

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8. Equations

1. $\Gamma_{out} = \dfrac{\dot{m}_{out}}{\pi\, d_i\, n_{tubes}}$

2. $Q = UA\Delta T$

3. $\Delta T_b = \dfrac{-RT_{wb}^2 \ln a_w}{\Delta h_v}$

4. $U = \dfrac{\Delta h_v\, \dot{m}_{evap}}{\pi\, d_i\, L\, \Delta T}$

5. $\dfrac{1}{U} = \dfrac{1}{h_i} + \dfrac{t}{k_s} + \dfrac{d_o}{d_i\, h_o}$

6. $h_i = \dfrac{U\, k_s d_i\, h_o}{k_s d_i\, h_o - d_i\, h_o U\, t - U\, k_s d_o}$

7. $h_o = k_l \left(\dfrac{g\rho_l^2}{\mu_l^2} \right)^{1/3} \left[Re_L^{-0.44} + 5.82 \times 10^{-6}\, Re_L^{0.8}\, Pr_l^{1/3} \right]^{1/2}$

8. $Re_L = \dfrac{4\Gamma_L}{\mu_L}$

9. $\Gamma_L = \dfrac{\dot{m}_{evap}}{\pi\, d_o\, n_{tubes}}$

10. $\Gamma_{min} = 1.69 \left(\dfrac{\mu_l \rho_l}{g} \right)^{1/5} \left[\sigma_l (1 - \cos\theta) \right]^{3/5}$

11. $\Gamma_{min} = 1.5788 \left[\sigma_l (1 - \cos\theta) \right]^{3/5} \left(\dfrac{\mu_l \rho_l}{g} \right)^{1/5}$

12.
$$\frac{\rho_l}{15} \left[\frac{g(\rho_l - \rho_v)}{\mu_l} \right]^2 \delta_{min}^{\;4} = \frac{\sigma_l (1 - \cos\theta)}{\delta_{min}} + (\gamma) \frac{q/A}{k_l} \cos\theta + \rho_v \left[\frac{q/A}{\rho_v \Delta h_v} \right] \frac{(\rho_l - \rho_v)}{\rho_l} \cos^2\theta$$

13. $\Gamma_{min} = \dfrac{\delta_m^{\;3} g (\rho_l - \rho_v)^2}{3\mu_l}$

14. $\Gamma_{min} = 1.12 \left(\sigma_l (1 - \cos\theta) \right)^{3/5} \left(\dfrac{\mu_l \rho_l}{g} \right)^{1/5}$

15. $\Gamma_{min} = 1.0179\left(\frac{\rho_l \mu_l}{g}\right)^{1/5} \left(\sigma(1-\cos\theta)\right)^{3/5}$

16. $\sigma[1-\cos\theta] = \frac{\rho_l g}{4}\left[\frac{\delta_{min}}{1-\cos\theta}\right]^2 [2\theta - \sin(2\theta)] + \frac{\rho_l^{\,3} g^2 (\delta_{min})^5}{15\mu_l^{\,5}}$

17. $\Gamma_{min} = \frac{\rho_l^{\,2} g (\delta_{min})^3}{3\mu_l}$

18. $\Gamma_{min} = 3.80\text{x}10^5 \ \mu_l^{\,0.24} \ \rho_l^{\,-1.66} \left(\sigma(1-\cos\theta)\right)^{3/5}$

19. $\mathrm{A} = \pi \, \mathrm{d_i} \ \mathrm{L} \ \mathrm{n_{tubes}}$

20. $\Delta\mathrm{T} = \mathrm{T_{shell}} - \mathrm{T_{effect}}$

21. $\mathrm{TS_{av}} = \frac{\mathrm{TS_{in}} + \mathrm{TS_{out}}}{2}$

22. $\dot{\mathrm{m}}_{\mathrm{out}} = \frac{\mathrm{TS_{in}} \ \dot{\mathrm{m}}_{\mathrm{in}}}{\mathrm{TS_{out}}}$

23. $\dot{\mathrm{m}}_{\mathrm{evap}} = \dot{\mathrm{m}}_{\mathrm{in}} \mathrm{TS_{feed}} \left(\frac{1}{\mathrm{TS_{in}}} - \frac{1}{\mathrm{TS_{out}}}\right) - \dot{\mathrm{m}}_{\mathrm{flash}}$

24. $\dot{\mathrm{m}}_{\mathrm{flash}} = \dot{\mathrm{m}}_{\mathrm{in}} \frac{\mathrm{TS_{feed}}}{\mathrm{TS_{in}}} \mathrm{Cp_{milk}} \left(\mathrm{T_{effect}} - \mathrm{T_{enter}}\right)$

25. $-\frac{dP}{dx} = \left(\frac{2fG^2 v_v}{D} + 2v_v G\left(\frac{4U\Delta T}{D\Delta h_v}\right) + \frac{g}{v_v}\right) \Big/ \left(1 + G^2 \frac{dv_G}{dP}\right)$

26. $\Gamma_{low,out} = \frac{\dot{\mathrm{m}}_{\mathrm{out}}}{\mathrm{n_{holes}} \ \pi \ \mathrm{d_i}}$

27. $\mathrm{U_{skim}} = -5463 \, \mathrm{TS} + 3247$

28. $\mathrm{U_{whole}} = -5441 \, \mathrm{TS} + 3382$

29. $\dot{\mathrm{m}}_{\mathrm{vap}} = \frac{\mathrm{U} \frac{\pi}{4} \mathrm{d_i^2} \ \mathrm{n_{tubes}} \Delta\mathrm{T}}{\Delta\mathrm{h_v}}$

30. $\frac{\dot{\mathrm{m}}_{\mathrm{vap}}}{\mathrm{n_{tubes}}} = \frac{\mathrm{U} \frac{\pi}{4} \mathrm{d_i^2} \ \mathrm{n_{tubes}} \Delta\mathrm{T}}{\Delta\mathrm{h_v}}$

Appendices

A-1. Evaporator run lengths

Table A-24: The evaporator run lengths for skim milk, whole milk and MPCs during the entire 2003-2004 milk powder season.

Run Length (hours)	Number of runs for: Skim Milk	Whole Milk	MPC-85 & MPC-70	Total
0 to 0.99	4	0	0	4
1 to 1.99	1	0	3	4
2 to 2.99	1	0	1	2
3 to 3.99	5	0	3	8
4 to 4.99	6	3	14	23
5 to 5.99	7	2	5	14
6 to 6.99	13	2	10	25
7 to 7.99	23	3	9	35
8 to 8.99	28	1	11	40
9 to 9.99	32	1	29	62
10 to 10.99	30	4	29	63
11 to 11.99	66	7	17	90
12 to 12.99	61	7	8	76
13 to 13.99	65	4	9	78
14 to 14.99	64	7	4	75
15 to 15.99	105	6	3	114
16 to 16.99	96	7	2	105
17 to 17.99	105	38	2	145
18 to 18.99	79	24	0	103
19 to 19.99	38	5	2	45
20 to 20.99	20	1	0	21
21 to 21.99	30	7	0	37
22 to 22.99	17	13	0	30
23 to 23.99	21	15	0	36
24 to 24.99	15	8	0	23
25 to 25.99	11	1	0	12
26 to 26.99	3	0	0	3
27 to 27.99	3	0	0	3
28 to 28.99	3	0	0	3
29 to 29.99	0	0	0	0
30 to 30.99	0	0	0	0
31 to 31.99	1	0	0	1

A-2. “Wetting Rig” single tube minimum wetting rates

Table A-25 and Table A-26 show the minimum wetting rates of distilled water and for reconstituted unstandardised skim milk, whole milk and MPC-85. These were under isothermal, heat transfer and evaporation conditions at 60ºC. The results shown are from this project, Tandon (2004) and Riley (2004). The correlation from Hartley and Murgatroyd (1964) was used by tendon (2004) to predict the minimum wetting rates at 60ºC.

Table A-25: Wetting rate measurements for distilled water and skim milk.

Substance	Condition	This project $kg\ m^{-1}s^{-1}$	Hartley & Murgatroyd (1964) $kg\ m^{-1}s^{-1}$	Tandon (2004) $kg\ m^{-1}s^{-1}$	Riley (2004) $kg\ m^{-1}s^{-1}$
Distilled water	Isothermal	0.085	0.186	0.147	
		0.096		0.144	
		0.109		0.130	
		0.103		0.136	
		0.104			
	Heat Transfer	0.106		0.142	0.116
		0.112			0.170
		0.104			0.114
		0.130			
	Evaporation	0.111			0.105
		0.097			
		0.100			
Skim Milk 10%	Isothermal	0.104	0.162	0.159	
		0.105		0.160	
	Heat Transfer	0.109		0.164	
				0.166	
	Evaporation	0.185			
		0.162			
Skim Milk 40%	Isothermal	0.119	0.162	0.146	
		0.111			
	Heat Transfer	0.131		0.155	0.130
		0.133			
	Evaporation	0.202			
		0.170			
Skim Milk 50%	Heat Transfer	0.166			

Table A-26: Minimum wetting rates for reconstituted whole milk and MPC-85.

Substance	Condition	This project kg m^{-1}s^{-1}	Comments
Whole Milk 10%	Isothermal	0.144	
		0.136	
	Heat Transfer	0.093	
		0.116	
		0.151	
		0.125	
	Evaporation	0.132	
		0.094	
		0.171	
Whole Milk 40%	Isothermal	0.174	
		0.143	
	Heat Transfer	0.167	
		0.161	
	Evaporation	0.167	
Whole Milk 50%	Heat Transfer	0.160	
MPC-85 10%	Isothermal	0.100	
		0.104	
	Heat transfer	0.113	
		0.115	
	Evaporation	0.170	
		0.174	
MPC-85 24%	Isothermal	0.128	
		0.121	
		0.111	
	Heat Transfer	0.206	
		0.190	
MPC-85 22%	Evaporation	0.203	Almost fully wet.

The following tables show the minimum wetting rate measurements according to the milk conditions. Table A-27 shows the isothermal measurements from this project, Table A-28 shows the minimum wetting rates under evaporation conditions and Table A-29 shows the measurements under atmospheric heat transfer conditions. Table A-30 shows the minimum wetting rates used in Figure 3-10. Uncertainties are provided.

Table A-27: Isothermal wetting rate measurements and uncertainties.

Concentration	Milk Type	Average Minimum Wetting Rate $kg\ m^{-1}s^{-1}$	Uncert-Ainty $kg\ m^{-1}s^{-1}$	Calibration Error $kg\ m^{-1}s^{-1}$
This project:				
0%	Distilled water	0.099	0.012	0.003
10%	Skim Milk	0.104	0.003	0.003
10%	Whole Milk	0.140	0.004	0.003
10%	MPC-85	0.102	0.003	0.003
24%	MPC-85	0.120	0.008	0.003
40%	Skim Milk	0.115	0.004	0.003
40%	Whole Milk	0.158	0.003	0.003
Tandon (2004):				
0%	Distilled water	0.139	0.008	0.003
10%	Skim Milk	0.162	0.004	0.003
40%	Skim Milk	0.146	–	0.003
Hartley & Murgatroyd (1964), (source: Winchester, 2000):				
0%	Used physical properties of skim milk To calculate minimum wetting rate	0.186		
5%		0.146		
10%		0.139		
20%		0.158		
30%		0.191		
40%		0.238		

Table A-28: Evaporation wetting rate measurements and uncertainties

Concentration	Milk Type	Average Minimum Wetting Rate $kg\ m^{-1}s^{-1}$	Uncert-ainty $kg\ m^{-1}s^{-1}$	Calibration Error $kg\ m^{-1}s^{-1}$
This project:				
0%	Distilled	0.103	0.007	0.003
10%	Skim	0.173	0.011	0.003
10%	Whole	0.151	0.020	0.003
10%	MPC-85	0.172	0.002	0.003
22%	MPC-85	0.203		0.003
40%	Skim	0.186	0.016	0.003
40%	Whole	0.167	0.003	0.003
Riley (2004):				
0%	Distilled	0.105		
40%	Skim	0.130		

Table A-29: Heat transfer measurements and uncertainties

Concentration	Milk Type	Average Minimum Wetting Rate kg $m^{-1}s^{-1}$	Uncert-ainty kg $m^{-1}s^{-1}$	Calibration Error kg $m^{-1}s^{-1}$
This project:				
0%	Distilled water	0.113	0.013	0.003
10%	Skim	0.109	0.003	0.003
10%	Whole	0.121	0.029	0.003
10%	MPC-85	0.114	0.001	0.003
24%	MPC-85	0.198	0.008	0.003
40%	Skim	0.132	0.003	0.003
40%	Whole	0.164	0.003	0.003
50%	Whole	0.160	0.003	0.003
50%	Skim	0.166	0.003	0.003
Tandon (2004):				
0%	Distilled	0.142	–	0.003
10%	Skim	0.165	–	0.003
40%	Skim	0.155	–	0.003
Riley (2004):				
0%	Distilled	0.133	0.028	0.003
40%	Skim	0.130	–	0.003
Hoke and Chen (2001) – Winchester (2004, personal communication)				
0%	Skim	0.231		
5%	Skim	0.140		
10%	Skim	0.133		
20%	Skim	0.143		
30%	Skim	0.154		
40%	Skim	0.125		

Table A-30: Data for Figure 3-10

Milk Type	Minimum Wetting Rates and Uncertainty [kg $m^{-1}s^{-1}$]		
	Isothermal	Heat Transfer	Evaporation
Distilled Water	0.099 ± *0.01*	0.113 ± *0.01*	0.103 ± *0.007*
10% Skim Milk	0.104 ± *0.003*	0.109 ± *0.003*	0.173 ± *0.01*
10% Whole Milk	0.140 ± *0.004*	0.121 ± *0.03*	0.151 ± *0.02*
10% MPC-85	0.102 ± *0.003*	0.114 ± *0.003*	0.172 ± *0.003*
22% MPC-85			0.203 ± *0.003*
24% MPC-85	0.120 ± *0.008*	0.198 ± *0.008*	
40% Skim Milk	0.115 ± *0.004*	0.132 ± *0.003*	0.186 ± *0.02*
40% Whole Milk	0.158 ± *0.003*	0.164 ± *0.003*	0.167 ± *0.003*
50% Skim Milk		0.166 ± *0.003*	
50% Whole Milk		0.160 ± *0.003*	

A-3 Opening of evaporators before cleaning

The evaporators were opened after running but before cleaning. Effects 3 and 4 of Evaporators 1 and 2 were opened after 22 hours of processing whole milk. Effects 2, 3 and 4 of Evaporator 4 were opened after 5 hours of MPC-85 production.

A-3.1 Whole milk in Evaporators 1 and 2 on 26 May 2004

Table A-31 shows the calculated wetting rates out of the underfed tubes in effects 3 and 4 of Evaporators 1 and 2. The evaporators were opened after running for 22 hours but before cleaning. Some tubes were fouled and others were clean. More photographs appear in A-14.1

Table A-31: The entry and exit total solids concentration of milk and the wetting rates of the underfed tubes in effects 3 and 4 after 22 hours of whole milk production in Evaporators 1 and 2.

	Total Solids %	Wetting Rate kg $m^{-1}s^{-1}$	Comments
Evaporator 1			
Into effect 3	42.7	0.242	Clean.
Out of Effect 3	46.0	0.225	Clean.
Into Effect 4	46.0	0.189	Clean.
Out of Effect 4	49.9	0.175	5 fouled tubes.
Evaporator 2			
Into effect 3	42.0	0.244	Clean.
Out of Effect 3	46.6	0.220	Clean.
Into Effect 4	46.6	0.186	Clean.
Out of Effect 4	52.3	0.165	25 fouled tubes.

A-3.2 MPC-85 in Evaporator 4 on 5 April 2005

Table A-32 shows the calculated wetting rates out of the underfed tubes in effects 2, 3 and 4 of Evaporators 4. The evaporator was opened after running for 5 hours but before cleaning. Some tubes were fouled and others were clean. The evaporator ran similarly to 15 March 2004 and approximate wetting rates were taken from total solids measurements of this run. More photographs appear in A-14.3.

Table A-32: The entry and exit total solids concentration of milk, and the wetting rates of the underfed tubes after 5 hours of MPC-85 production.

Effect–Pass	Estimated total solids %	Wetting Rate kg $m^{-1}s^{-1}$	Cleanliness
In 2-1	15.0	0.123	Clean tubes. Upward vapour flows.
Out of 2-5	24.3	0.204	Clean tubes.
Into 3-1	24.3	0.269	Clean tubes.
Out of 3-1	25.0	0.261	Clean, but fouled at top.
Into 4-1	25.0	0.220	No fouled tubes. No holes blocked.
Out of 4-1	25.7	0.214	No fouled tubes.

The distribution plates were filthy in all passes, with chunks blocking many holes. See A-14.2 and A-14.3 for photographs of MPC fouling.

A-4. Hole diameters

The hole diameters measured in the evaporators are shown in Table A-33 and Table A-34. Niro supplied drawings which showed the intended hole sizes in the ED3 evaporators.

Table A-33: Average Measured Hole Diameters

Plant	**Evaporator**	**Hole size in effect–pass [mm]**								
		1-1	**1-2**	**2-1**	**2-2**	**2-3**	**2-4**	**2-5**	**3-1**	**4-1**
CD1	1	5.6	5.7	6.0	6.0	5.9	6.8	6.1	7.7	6.4
	2	5.7	5.7	6.2	6.1	5.6	6.5	6.0	7.2	6.1
CD2	3	5.8	5.6	6.2	6.2	5.7	6.8	6.8	8.0	7.0
	4	5.8	5.6	6.1	6.3	5.6	6.7	6.8	8.0	6.7
	5	5.9	5.6	6.1	6.1	6.0	6.9	6.9	7.8	7.0
ED2	3								8.2	6.9
	4								8.2	
ED3	5	5.9	5.7	6.2	6.1	6.0	6.9	6.8	8.0	6.9
	6	6.0	5.7	6.4	6.4	6.0	7.1	7.0	7.9	7.0
	7	5.9	5.9	6.3	6.3	5.9	6.9	7.0	8.0	7.0

Table A-34: Uncertainties of average measured hole diameters

Plant	Evaporator	Hole size in effect–pass [mm]								
		1-1	1-2	2-1	2-2	2-3	2-4	2-5	3-1	4-1
CD1	1	0.2	0.1	0.2	0.1	0.15	0.2	0.2	0.2	0.1
	2	0.2	0.1	0.2	0.2	0.3	0.4	0.2	0.1	0.2
CD2	3	0.2	0.2	0.1	0.1	0.1	0.1	0.2	0.1	0.1
	4	0.2	0.2	0.1	0.02	0.2	0.2	0.1	0.1	0.3
	5	0.1	0.1	0.1	0.1	0.05	0.1	0.2	0.1	0.05
ED2	3								0.05	0.05
	4								0.2	
ED3	5	0.1	0.15	0.1	0.1	0.05	0.15	0.2	0.2	0.1
	6	0.05	0.05	0.01	0.05	0.35	0.35	0.05	0.05	0.05
	7	0.01	0.01	0.22	0.05	0.05	0.1	0.05	0.25	0.1

A-5. Wetsuit job results

The wetsuit job was performed Tuesday 27 July 2004 by Steve Broome and was assisted by John Gabites. Table A-35 to Table A-38 show the flows measured and the calculations of the relative flows into each tube with their respective uncertainties. Some flows were adjusted to account for holes which were mistakenly blocked. This was in tubes 1, 4 and 8 of effect 3, and for tubes 1, 6 and 11 of effect 4. Adjusted flows are shown in bold type. The half error was half the range of values in each data set. Table A-39 shows the water flowrates from the hoses.

Table A-35: Niro Distribution Plate in Effect 3

Tube	Measured Flows					Uncertainties		Relative flows		
	a	b	c	Mean	Adjustment	Half Error ±	Calibration Error ±	Expected	Measured	±
1	34.3	34.3	35.7	35	**52**	0.7	1.4	2.0	1.8	0.07
2	39.6	40.0	39.2	40	40	0.4	1.7	1.3	1.4	0.06
3	40.4	38.8	38.8	39	39	0.8	1.8	1.3	1.4	0.06
4	25.6	24.4	24.7	25	**40**	0.6	0.9	1.3	1.4	0.05
5	–	–	–	–	–	–	–	–	–	–
6	31.7	31.3	31.0	31	31	0.3	1.2	1.0	1.1	0.04
7	40.8	37.5	38.3	39	39	1.7	1.8	1.2	1.3	0.06
8	25.3	23.9	25.0	25	**40**	0.7	0.9	1.3	1.4	0.05
9	30.3	30.7	29.7	30	30	0.5	1.2	1.0	1.0	0.04
10	30.3	28.7	31.3	30	30	1.3	1.2	1.0	1.0	0.04
11	26.9	27.2	25.3	26	26	1.0	0.9	1.0	0.9	0.03
12	30.3	30.0	29.0	30	30	0.7	1.1	1.0	1.0	0.04
13	31.7	32.9	33.7	33	33	1.0	1.3	1.0	1.1	0.05

Table A-36: Acrylic Distribution Plate in Effect 3

Tube	Measured Flows				Uncertainties		Relative flows		
	a	b	c	Mean	Half Error ±	Calibration Error ±	Expected	Measured	±
1	25.0	25.0	24.7	25	0.2	1.0	1.0	0.8	0.03
2	31.7	31.0	30.3	31	0.8	1.2	1.0	0.8	0.03
3	33.0	31.0	32.0	32	1.0	1.3	1.0	0.8	0.03
4	28.7	28.3	26.7	28	1.0	1.1	1.0	0.9	0.03
5	–	–	–	–	–	–	–	–	–
6	35.7	36.1	36.4	36	0.4	1.5	1.0	0.9	0.04
7	37.7	35.0	38.5	37	1.7	1.6	1.0	1.0	0.04
8	34.2	32.7	32.7	33	0.8	1.5	1.0	1.0	0.04
9	37.3	36.9	36.2	37	0.6	1.6	1.0	0.9	0.04
10	38.8	36.9	38.5	38	1.0	1.7	1.0	1.0	0.04
11	37.3	36.5	37.3	37	0.4	1.6	1.0	1.0	0.04
12	38.1	39.6	38.8	39	0.8	1.7	1.0	1.0	0.04
13	37.3	36.9	38.5	38	0.8	1.6	1.0	1.0	0.04

Table A-37: Niro Distribution Plate in Effect 4

Tube	Measured Flows					Uncertainties		Relative flows		
	a	b	c	Mean	Adjust ment	Half Error ±	Calibration Error ±	Expect ed	Meas ured	±
1	19.3	17.5	19.8	19	**30.5**	1.1	0.6	1.3	1.3	0.04
2	24.4	25.8	25.6	25	25	0.7	0.9	1.0	1.1	0.04
3	22.3	22.0	22.7	22	22	0.3	0.9	1.0	1.0	0.04
4	33.3	35.7	34.7	35	35	1.2	1.4	1.0	1.2	0.05
5	–	–	–	–	–	–	–	–	–	–
6	19.3	20.8	20.3	20	**31.5**	0.8	0.7	1.3	1.3	0.04
7	22.8	21.5	22.0	22	22	0.6	0.7	1.0	1.0	0.03
8	23.8	22.8	23.0	23	23	0.5	0.8	1.0	1.0	0.03
9	28.7	27.7	28.3	28	28	0.5	1.1	1.0	1.2	0.05
10	22.8	22.8	22.0	23	23	0.4	0.7	1.0	1.0	0.03
11	22.0	21.3	21.8	22	**33.5**	0.4	0.7	1.3	1.5	0.05
12	24.0	24.5	24.0	24	24	0.3	0.8	1.0	1.1	0.03
13	23.5	22.5	22.8	23	23	0.5	0.7	1.0	1.0	0.03

Table A-38: Acrylic Distribution Plate in Effect 4

Tube	Measured Flows				Uncertainties		Relative flows		
	a	b	c	Mean	Half Error ±	Calibration Error ±	Expect ed	Meas ured	±
1	22.3	22.5	22.5	22	0.1	0.7	1.0	0.8	0.02
2	31.0	28.7	30.7	30	1.2	1.2	1.0	0.8	0.03
3	39.2	36.3	32.5	36	3.3	1.7	1.0	0.9	0.04
4	47.5	48.0	49.0	48	0.8	2.6	1.0	1.2	0.07
5	–	–	–	–	–	–	–	–	–
6	26.0	25.7	24.7	25	0.7	1.0	1.0	0.8	0.03
7	34.7	34.2	35.0	35	0.4	1.5	1.0	0.9	0.04
8	36.3	37.5	35.4	36	1.0	1.7	1.0	0.9	0.04
9	35.0	35.4	34.6	35	0.4	1.6	1.0	0.9	0.04
10	35.4	33.3	33.3	34	1.0	1.6	1.0	0.9	0.04
11	29.2	27.5	27.9	28	0.8	1.3	1.0	0.9	0.04
12	37.5	35.8	35.8	36	0.8	1.7	1.0	0.9	0.04
13	35.0	33.3	34.2	34	0.8	1.6	1.0	0.9	0.04

Table A-39: Inlet flow of water form the hoses.

Measurement	Value	Uncertainty
Tare jar	255 g	± 5 g
Time	3.0 s	± 0.5 s
Water tap 1	2300 g	± 5 g
Water tap 2	1920 g	± 5 g
Total water	4220 g	± 55 g
Total flow	1407 g s^{-1}	± 235 g s^{-1}

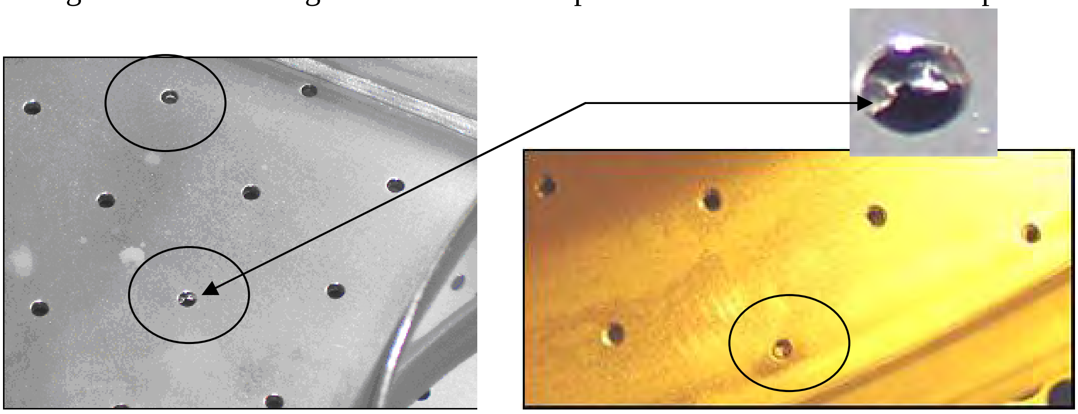
$$\text{Uncertainty} = \left(1407\text{ g s}^{-1}\right)\sqrt{\left(\frac{55g}{4220g}\right)^2 + \left(\frac{0.5\text{ s}}{3.0\text{ s}}\right)^2} = 235\text{ g s}^{-1}$$

A-6. Faults in distribution plates

The following faults in the distribution plates were found and documented.

A-6.1 Problems with holes

A small number of holes were blocked by what appears to be welding material (Figures A-1a, A-1b and A-2). This can restrict the flowrates into the tubes, affecting wetting rates and cleaning. These were in Evaporators 5 of the CD2 and ED3 plants.



Figures A-1a and A-1b **Figure A-2**

Figures A-1 and A-2: Metal in some holes in CD2 Evaporator 5 effect 2 pass 5 (left) and ED3 Evaporator 5 effect 1 pass 1 (right).

Sometimes fabricators continued the hole pattern by one extra hole (figures A-3 and A-4). This was seen in some ED3 and CD2 evaporators.

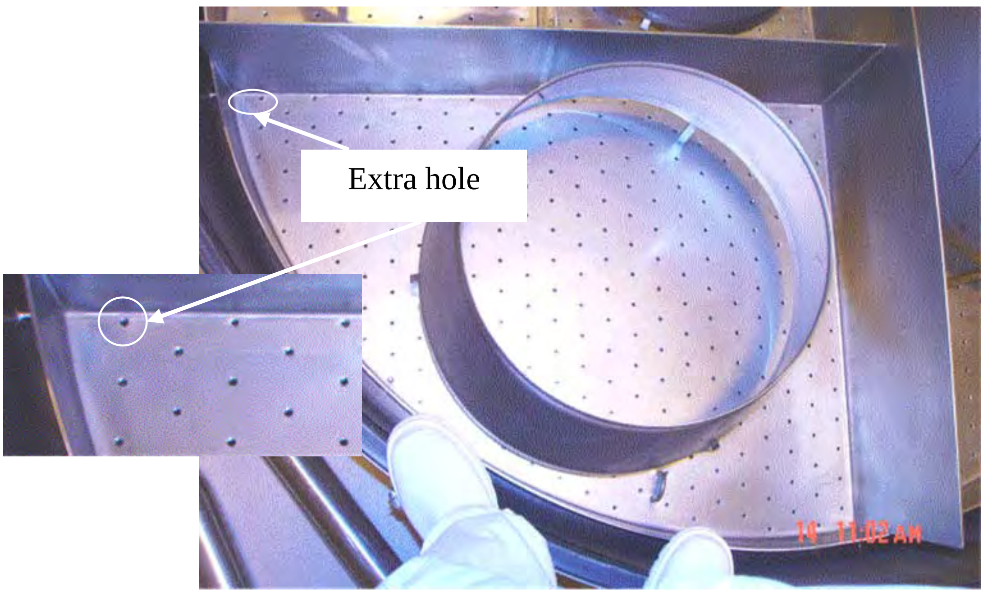


Figure A-3: Extra hole in effect 2 pass 2 which does not surround a tube – found in ED3 Evaporators 5, 6 and 7 and CD2 Evaporators 3 and 4.

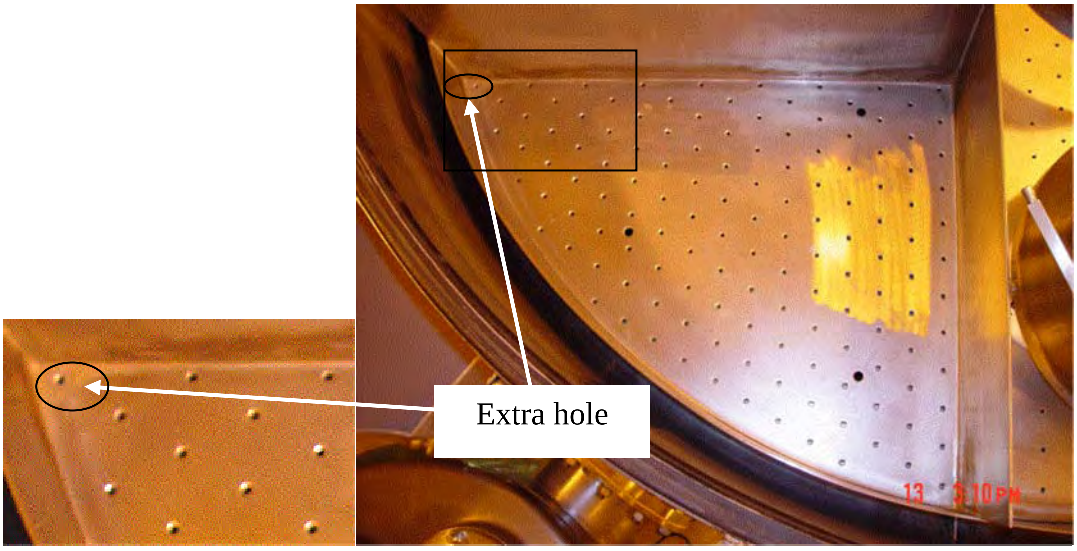


Figure A-4: Extra hole in effect 2 pass 5 which does not surround a tube – found in Evaporators 5, 6 and 7 ED3. Not seen on CD1 or CD2 evaporators.

Evaporator 5 in CD2 had faults with holes being drilled. There was an extra hole in the middle of effect 2-5 (Figure A-5). The missing hole in effect 3 in Figure A-6 was punched but never drilled.

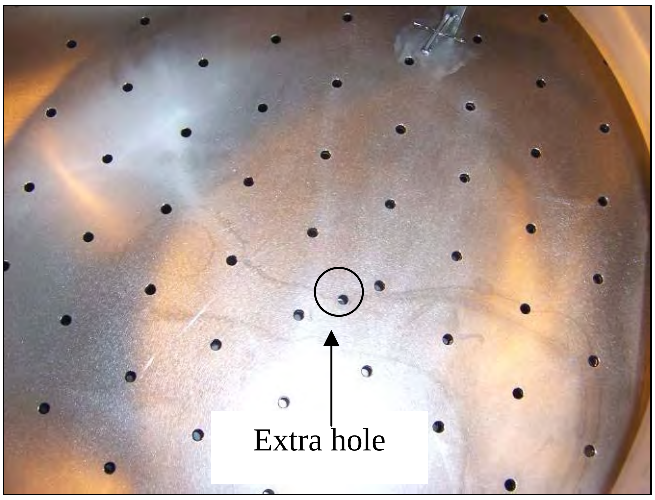


Figure A-5: An 'extra' hole drilled into CD2 evaporator 5 effect 2 pass 5.

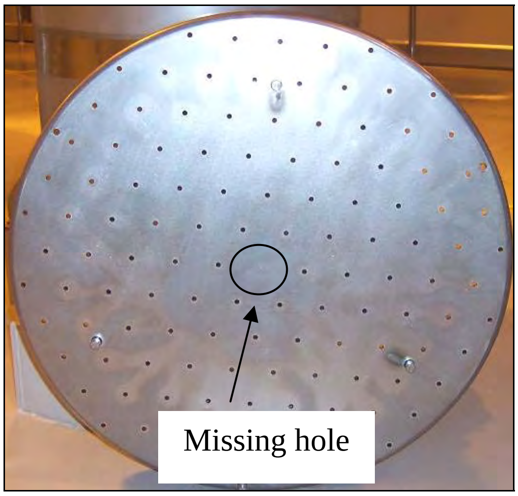


Figure A-6: A 'missing' hole in CD2 Evaporator 5 effect 3.

A-6.2 Misalignment and warping of distribution plates

Figures A-7 and A-8 show how misalignment was measured. Figures A-9 and A-10 demonstrate how warping was measured. The reported warping is the difference between the maximum and minimum heights (the range). Plates with height variations of 4.0 mm or more were considered to be warped.

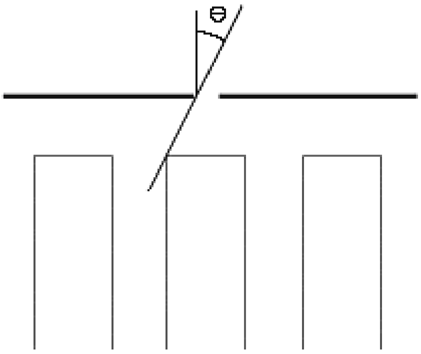


Figure A-7: Angles identical (ok)

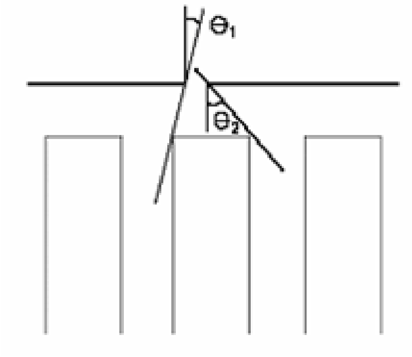


Figure A-8: Angles vary (misaligned).

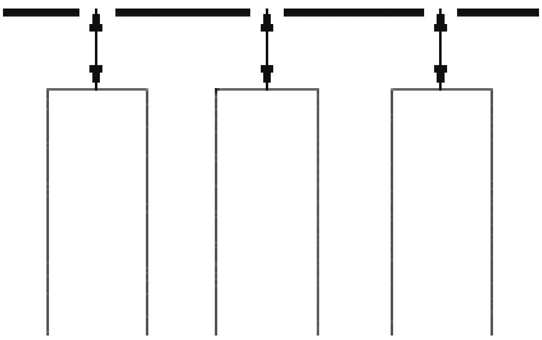


Figure A-9: Perfectly flat and level distribution plates have the same heights between the tubesheet and the top of the distribution plate.

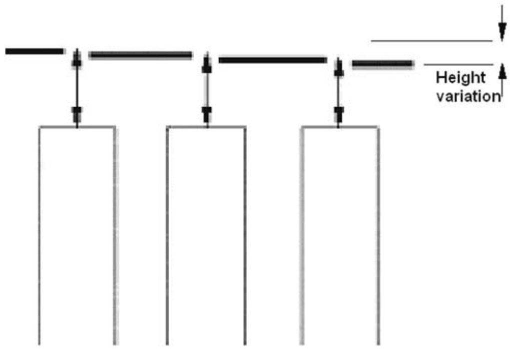


Figure A-10: Warped distribution plates have different heights between the tubesheet and the top of the distribution plate.

Table A-40 details all the fabrication faults found in the Edendale and Clandeboye evaporators. The following pages show the measurements taken for each evaporator. The height values refer to the height of the distribution plate above the tubesheet. Puddles of water sometimes seen and indicated warping. The *Δh* refers to the range of heights.

Table A-40: Fabrication faults found in the Clandeboye and Edendale evaporators.

Plant	**Evaporator**	**Effect & Pass**	**Comments**
CD1	1	1-1	Warped – height variation 11.7 mm – sunk in middle.
		1-2	Warped – height variation 7.8 mm – sunk in middle.
		2-1	Warped – height variation 10.7 mm.
		2-2	Warped – height variation 13.1 mm – sunk in middle.
		2-3	Warped – height variation 4.6 mm.
		2-5	Warped – height variation 10.7 mm. Holes misaligned – hole partially above tube space.
		4-1	Hole sizes are 6.4 ± 0.1 mm (7.0 mm for ED3 and 6.1 mm in CD1 Evaporator 2).
	2	1-1	Warped – height variation 10.1 mm.
		1-2	Warped – height variation 5.6 mm.
		2-1	Warped – height variation 24.1 mm. Holes misaligned slightly.
		2-2	Warped – height variation 15.7 mm (sunken in middle). Holes misaligned slightly.
		2-5	Warped – height variation 19.4 mm. Holes misaligned slightly.
		3-1	Warped – height variation 5.9 mm – sunk on one side (not middle).
		4-1	Hole sizes are 6.1 mm (7.0 mm for ED3 and 6.4 mm in CD1 Evaporator 1).
CD2	3	2-2	Warped – height variation 8.9 mm. Extra hole by 2-4 corner.
		2-3	Warped – height variation 4.0 mm.
	4	1-1	Warped – height variation 11.9 mm – raised in middle.
		1-2	Warped – height variation 5.5 mm.
		2-2	Warped – height variation 12.7 mm. Extra hole by 2–4 corner. Slightly misaligned (1 mm edge of holes to edge nearest tube).
		2-3	Warped – height variation 5.5 mm.
		2-5	Warped – height variation 7.2 mm.
	5	1-1	Warped – height variation 9.0 mm – sunk in middle.
		1-2	Warped – height variation 8.0 mm – raised on edge. Several holes blocked by welding material.
		2-1	Warped – height variation 5.2 mm.
		2-2	Misaligned (hole partially above tube space).
		2-4	Warped – height variation 4.3 mm.
		3-1	Warped – height variation 6.1 mm – raised on side. Missing centre hole.
		4-1	Warped – height variation 4.2 mm – sunk in middle.
ED2	4	4-1	Warped – height variation 4.2 mm.
ED3	5	1-1	Warped – height variation 4.2 mm.
		1-2	Warped – height variation 8 mm
		2-2	Possibly extra hole in corner by 2–4.
		2-5	Possibly extra hole in corner by 2–1.
	6	1-1	Warped – height variation 5.5 mm.
		1-2	Warped – height variation 4 mm.
		2-2	Warped – height variation 8.0 mm. Holes slightly misaligned.
		2-5	Misaligned (hole partially above tube space).
	7	2-2	Warped – height variation 14.5 mm.
		2-3	Warped – height variation 6.1 mm.
		2-5	Warped – height variation 5.2 mm.

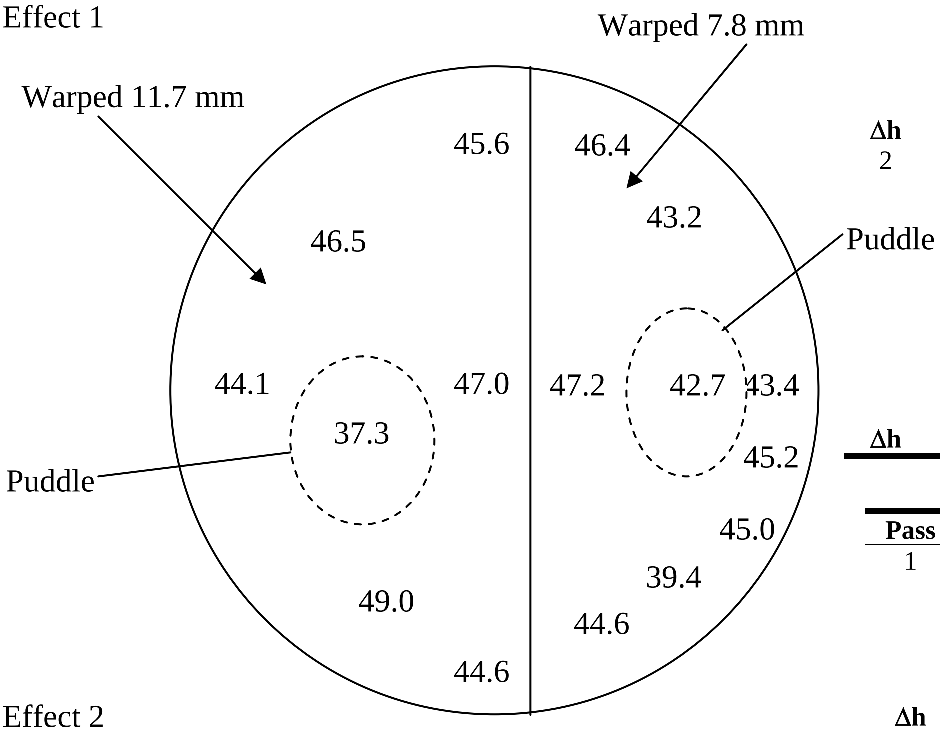
A-6.3 Distribution plates at Clandeboye

The following pages show warping and misalignment measurements. The height measured is from the top of the distribution plate to the top of the tubesheet. Numbers are reported in order of pass. A height variation over 4.0 mm was treated as warping.

CD1 Evaporator 1

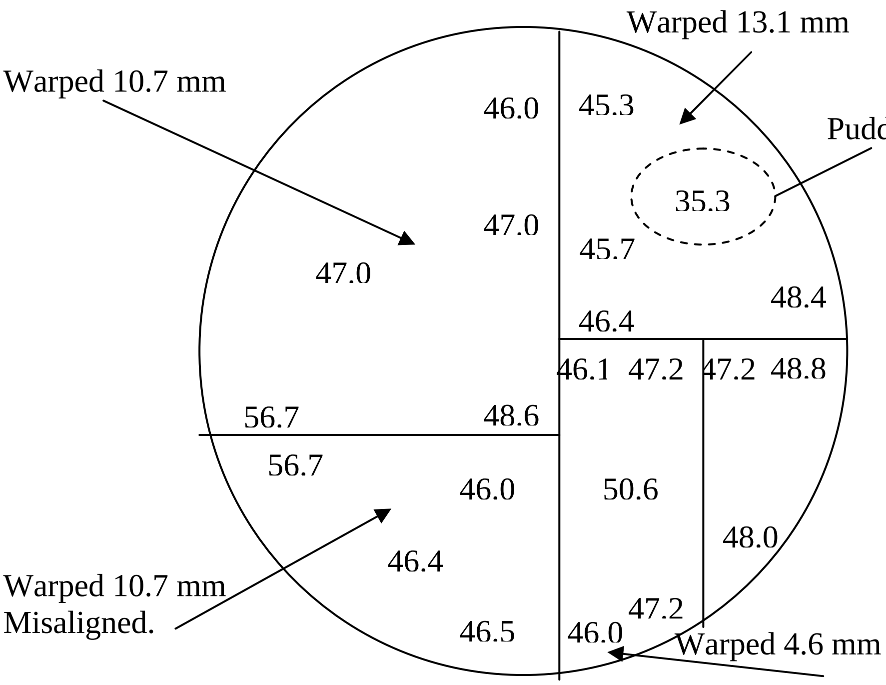
Pass	Height
1	45.6
	46.5
	44.1
	37.3
	47.0
	49.0
	44.6
Δh	**11.7**
2	46.4
	43.2
	47.2
	42.7
	43.4
	45.2
	45.0
	39.4
	44.6
Δh	**7.8**

Effect 1

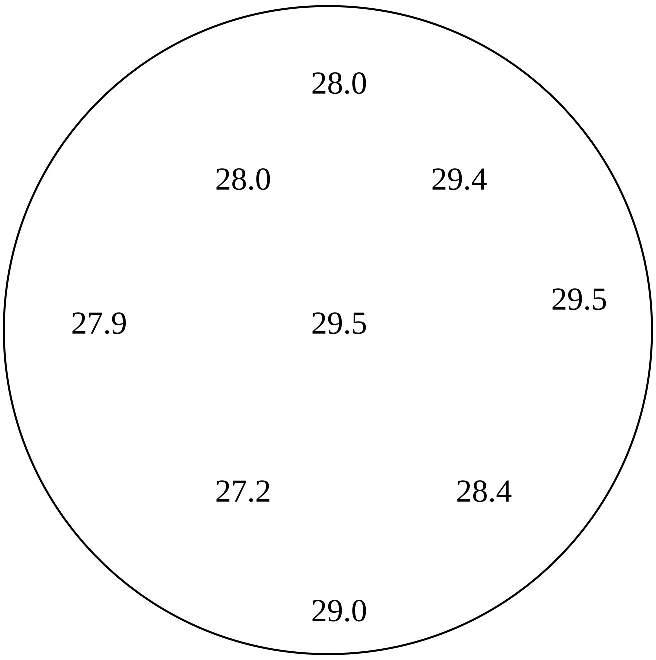


Pass	Height
1	46.0
	47.0
	47.0
	48.6
	56.7
Δh	**10.7**
2	45.3
	35.3
	45.7
	48.4
	46.4
Δh	**13.1**
3	46.0
	46.1
	50.6
	47.2
	47.2
Δh	**4.6**
4	47.2
	48.8
	48.0
Δh	**0.8**
5	56.7
	46.0
	46.4
	46.5
Δh	**10.7**

Effect 2



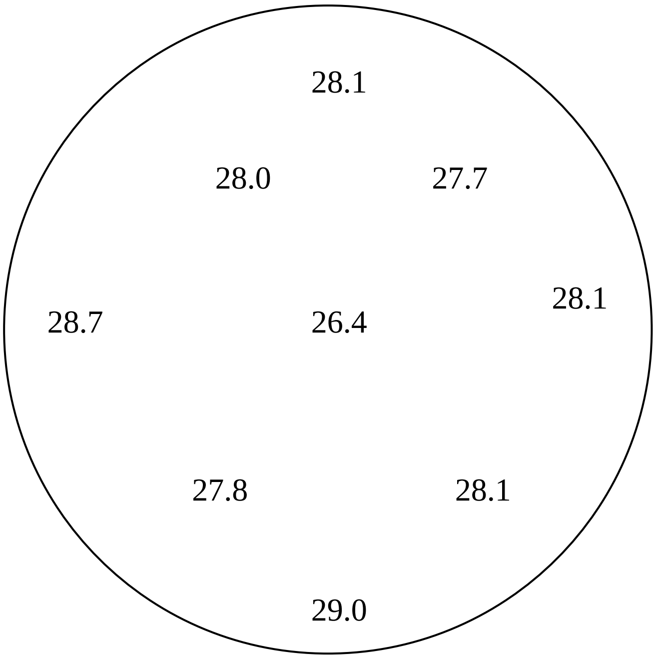
Effect 3



	Height
	28.0
	29.0
	27.9
	29.5
	29.5
	28.0
	29.4
	27.2
	28.4
Δh	**2.3**

Effect 4

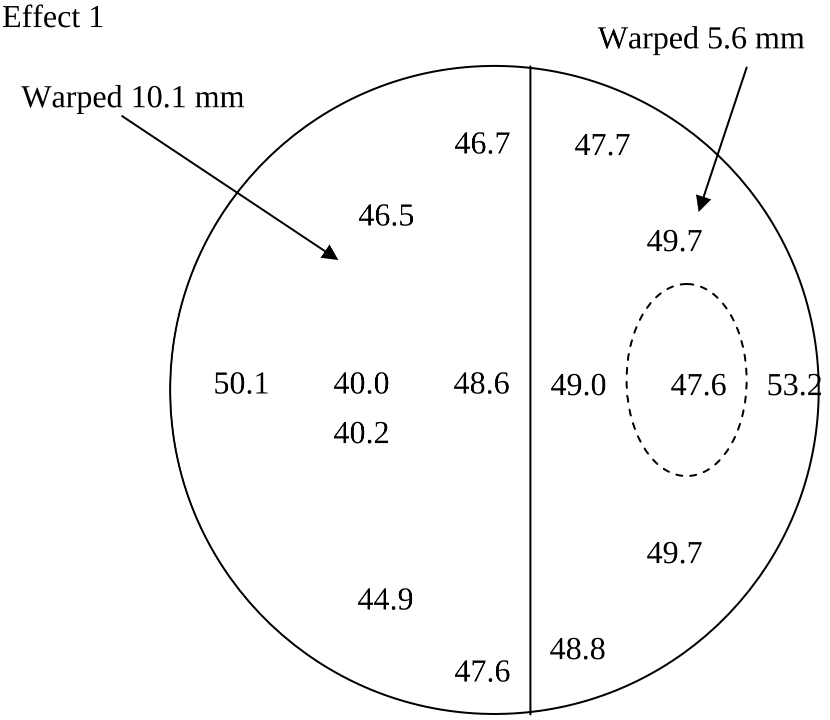
	Height
	28.1
	29.0
	28.7
	28.1
	26.4
	28.0
	27.7
	27.8
	28.1
Δh	**2.6**



Hole sizes are 6.4 mm instead of 7.0 mm.
Different to Evaporator 2.

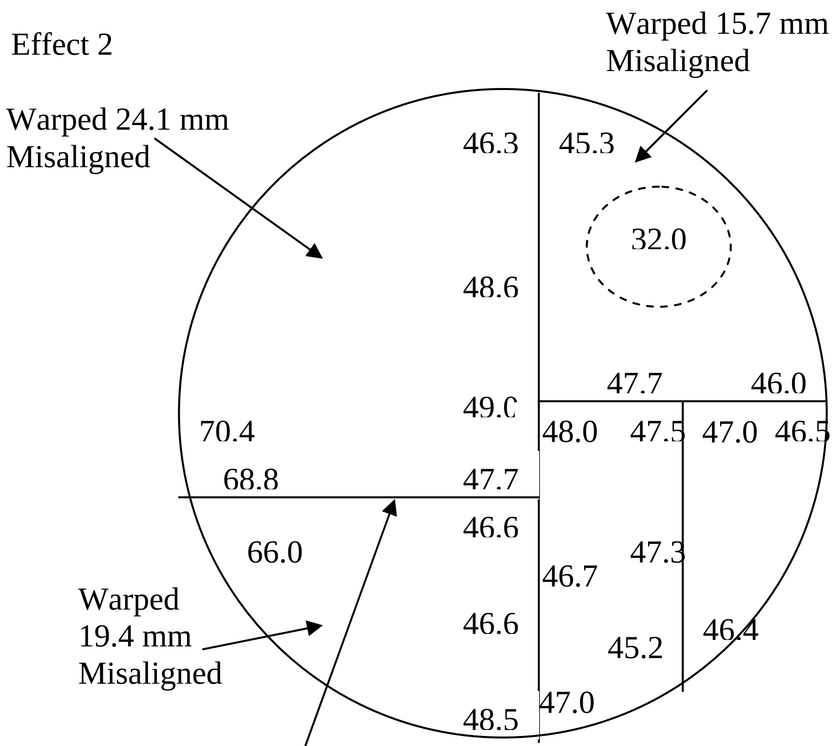
CD1 Evaporator 2

Effect 1



Pass	Height
1	467
	46.5
	50.1
	40.0
	48.6
	40.2
	44.9
	47.6
Δh	**10.1**
2	47.7
	49.7
	49.0
	47.6
	53.2
	49.7
	48.8
Δh	**5.6**

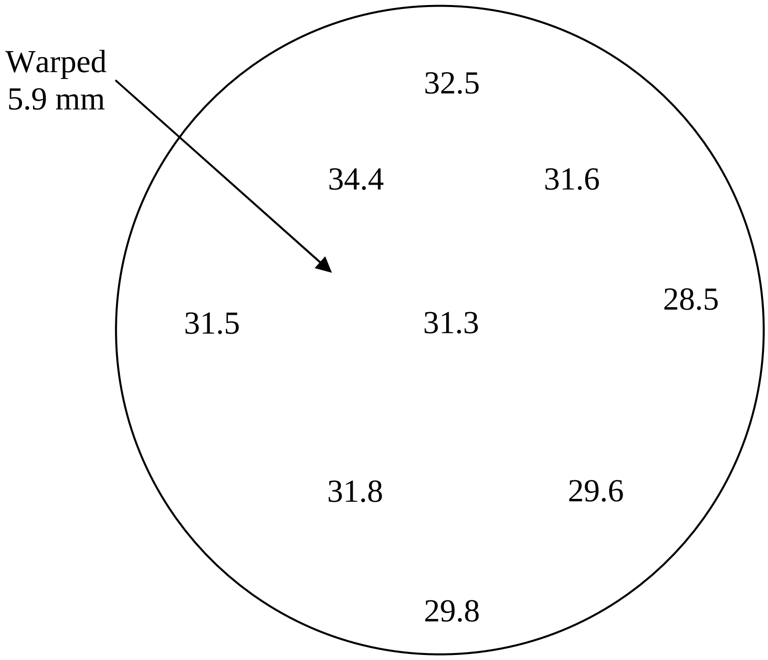
Effect 2



There is a ~30 mm gap between the 40 mm partitions and bottom of the distribution plate.
Vapour probably flows through this gap.
All other passes lie on the partitions.

Pass	Height
1	46.3
	48.6
	49.0
	70.4
	68.8
	47.7
Δh	**24.1**
2	45.3
	32.0
	47.7
	46.0
Δh	**15.7**
3	48.0
	47.5
	47.3
	46.7
	45.2
	47.0
Δh	**2.8**
4	47.0
	46.5
	46.4
Δh	**0.6**
5	46.6
	66.0
	46.6
	48.5
Δh	**19.4**

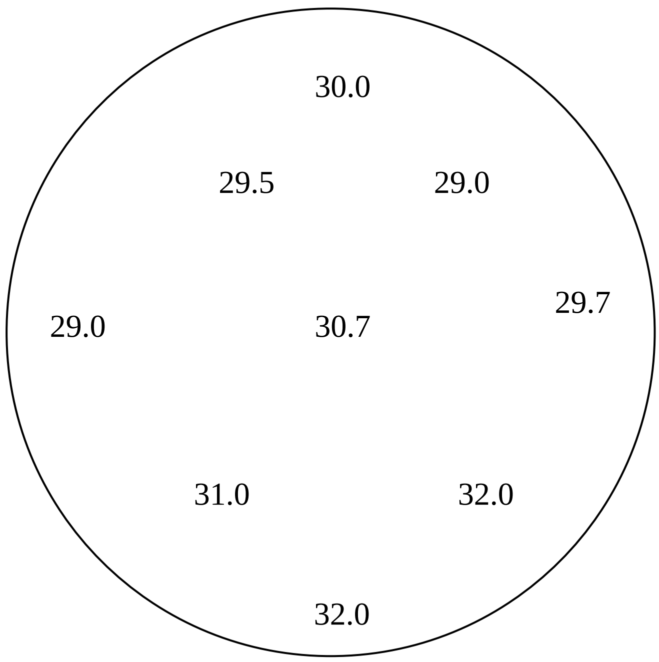
Effect 3



	Height
	32.5
	29.8
	31.5
	28.5
	31.3
	34.4
	31.6
	31.8
	29.6
Δh	**5.9**

Effect 4

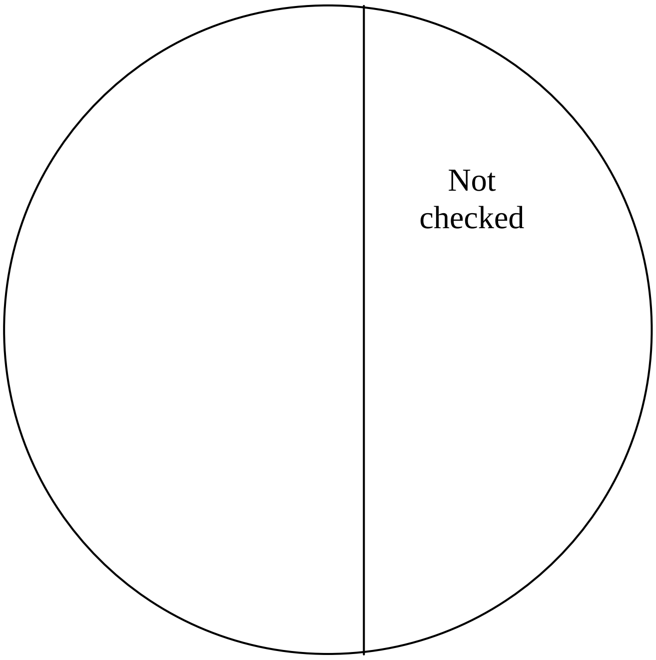
	Height
	30.0
	32.0
	29.0
	29.7
	30.7
	29.5
	29.0
	31.0
	32.0
Δh	**3.0**



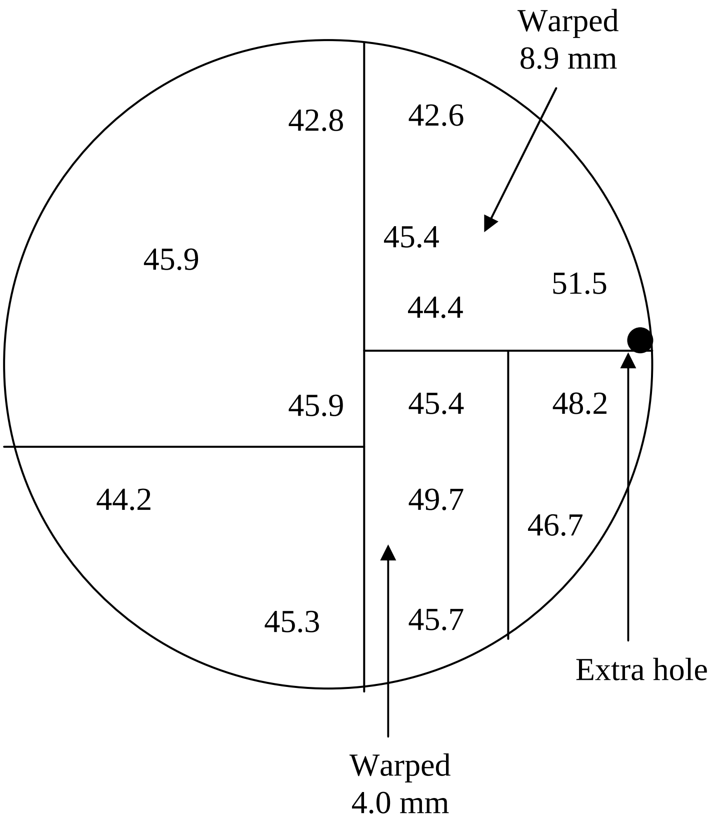
Hole sizes are 6.1 mm instead of 7.0 mm.
Different to Evaporator 1.

CD2 Evaporator 3

Effect 1

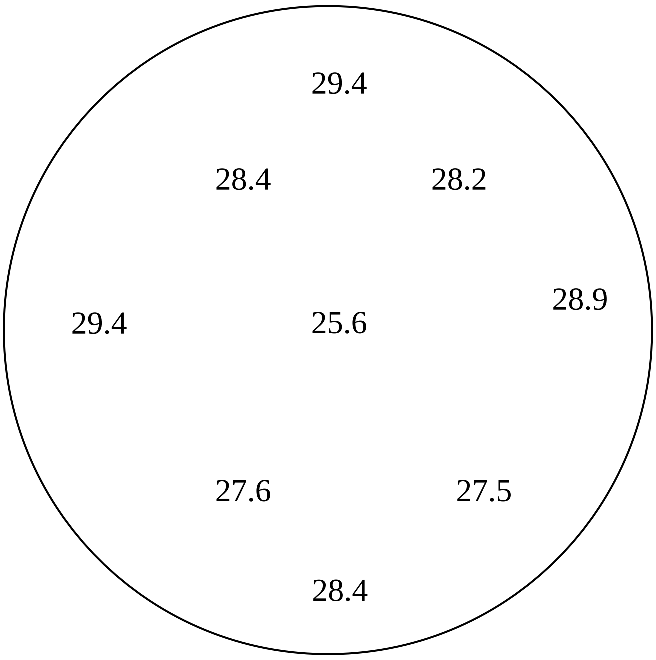


Effect 2



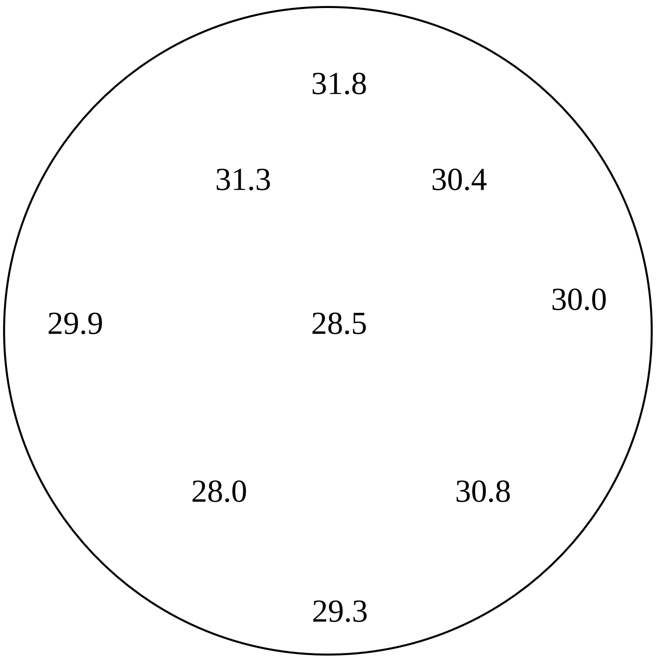
Pass	Height
1	42.8
	45.9
	45.1
Δh	**3.1**
2	42.6
	44.4
	51.5
	45.4
Δh	**8.9**
3	45.7
	49.7
	47.6
Δh	**4.0**
4	46.7
	48.2
Δh	**1.5**
5	44.2
	45.3
Δh	**1.1**

Effect 3



	Height
	29.4
	28.4
	29.4
	28.9
	25.6
	28.4
	28.2
	27.6
	27.5
Δh	**3.8**

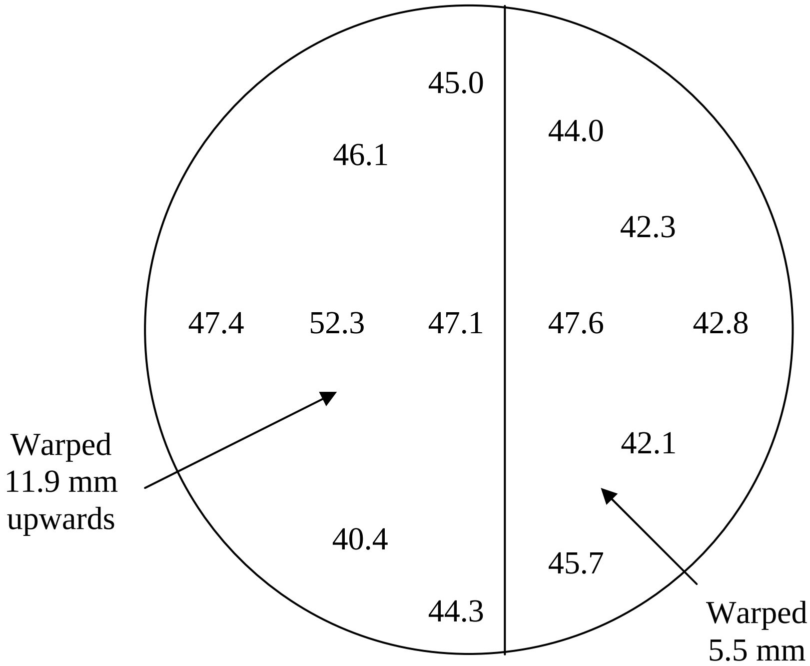
Effect 4



	Height
	31.8
	29.3
	29.9
	30.0
	28.5
	31.3
	30.4
	28.0
	30.8
Δh	**3.8**

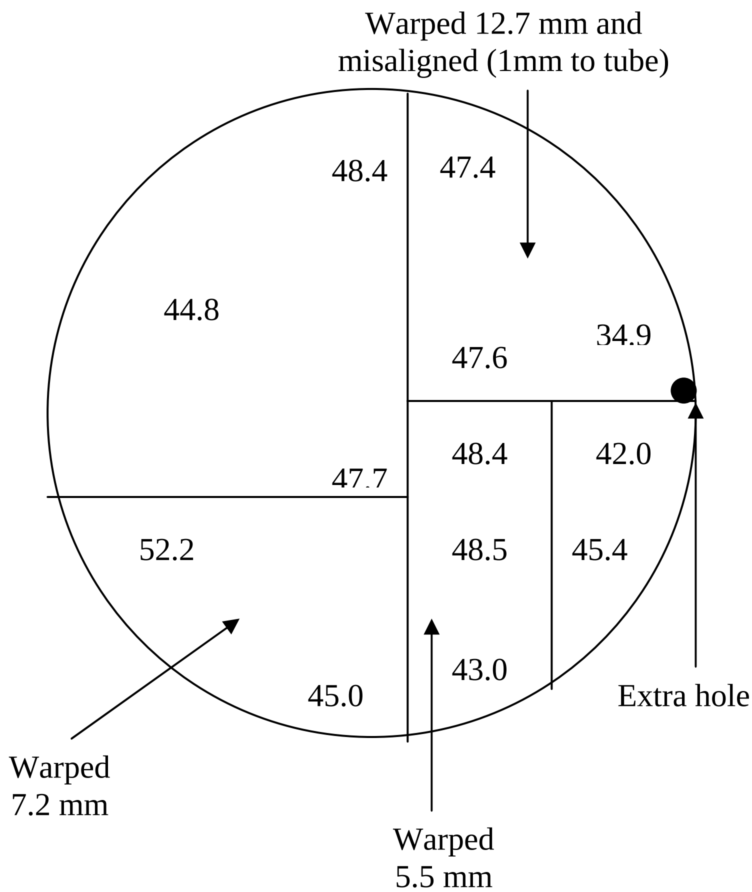
CD2 Evaporator 4

Effect 1



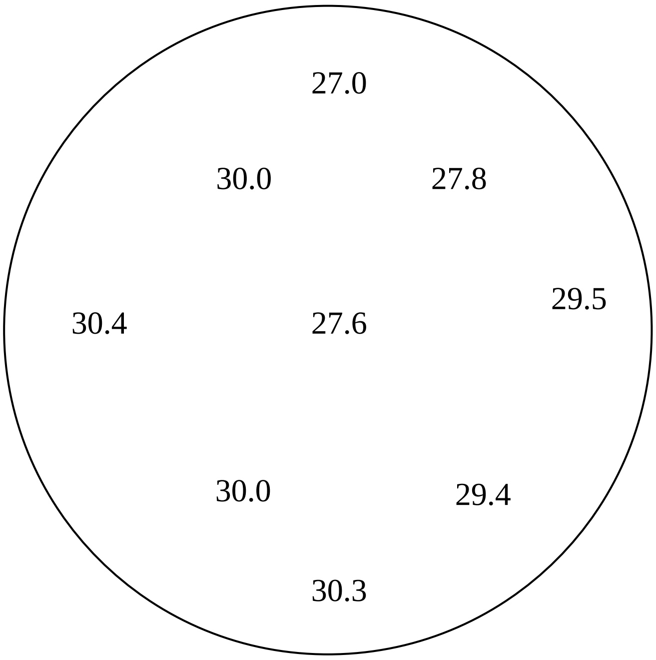
Pass	Height
1	45.0
	47.1
	44.3
	46.1
	52.3
	40.4
	47.4
Δh	**11.9**
2	44.0
	47.6
	45.7
	42.3
	42.1
	42.8
Δh	**5.5**

Effect 2



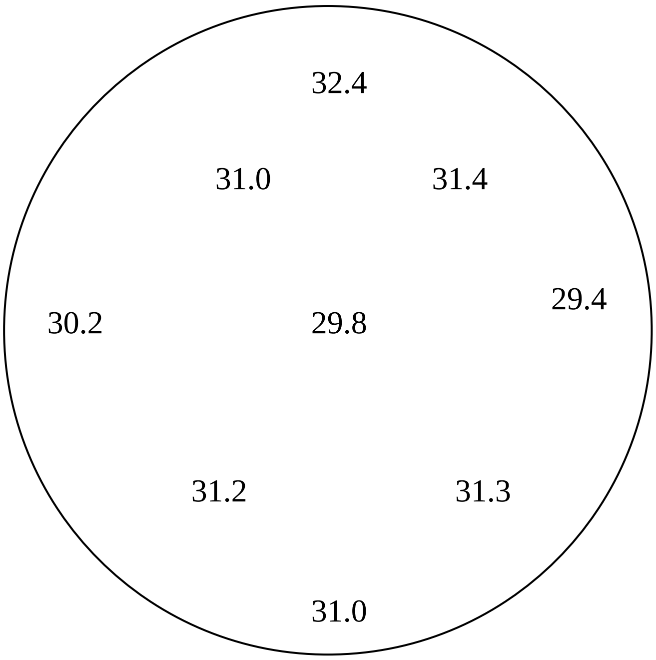
Pass	Height
1	48.4
	44.8
	47.7
Δh	**3.6**
2	47.4
	47.6
	34.9
Δh	**12.7**
3	43.0
	48.5
	48.4
Δh	**5.5**
4	45.4
	42.0
Δh	**3.4**
5	52.2
	45.0
Δh	**7.2**

Effect 3



	Height
	27.0
	30.3
	30.4
	29.5
	27.6
	30.0
	27.8
	30.0
	29.4
Δh	**3.4**

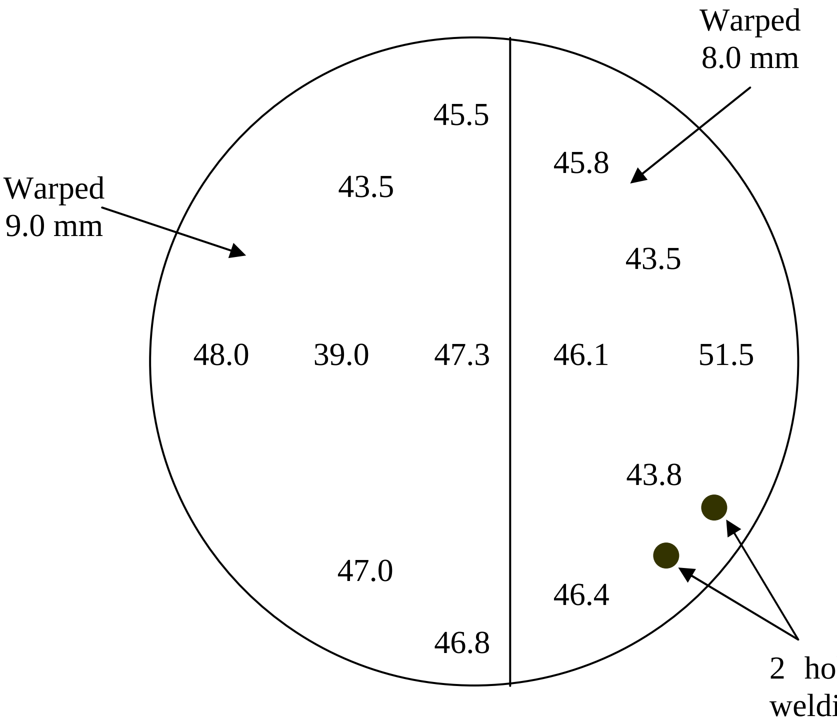
Effect 4



	Height
	32.4
	31.0
	30.2
	29.4
	29.8
	31.0
	31.4
	31.2
	31.3
Δh	**3.0**

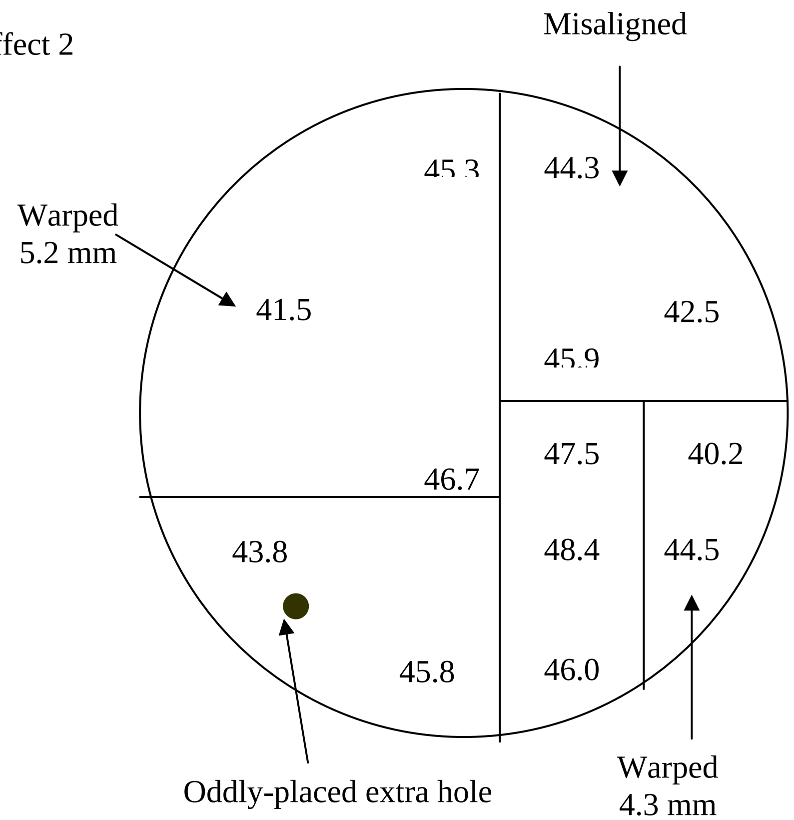
CD2 Evaporator 5

Effect 1



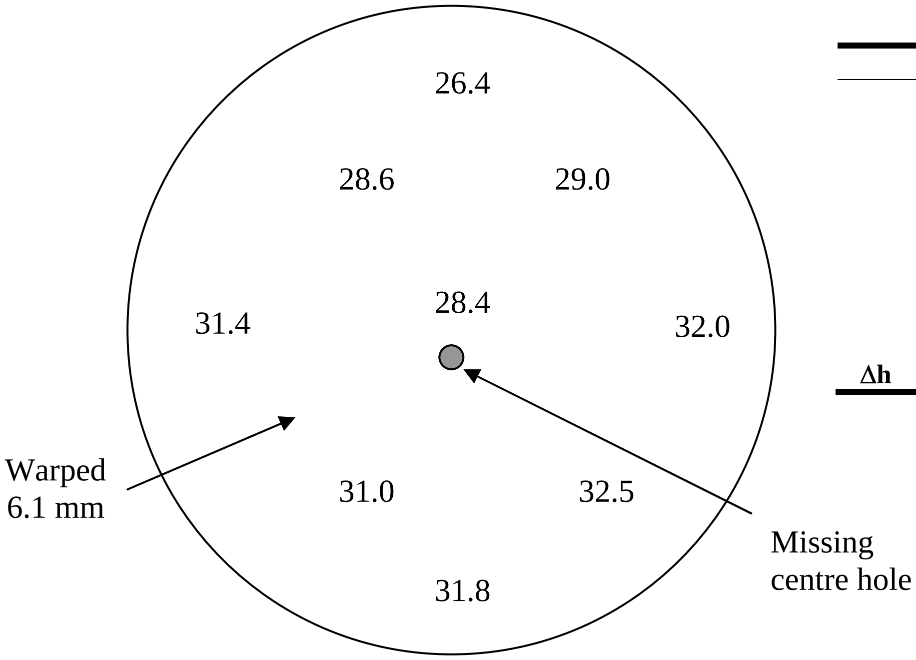
Pass	Height
1	45.5
	47.3
	46.8
	43.5
	39.0
	47.0
	48.0
Δh	**9.0**
2	45.8
	46.1
	46.4
	43.5
	43.8
	51.5
Δh	**8.0**

Effect 2



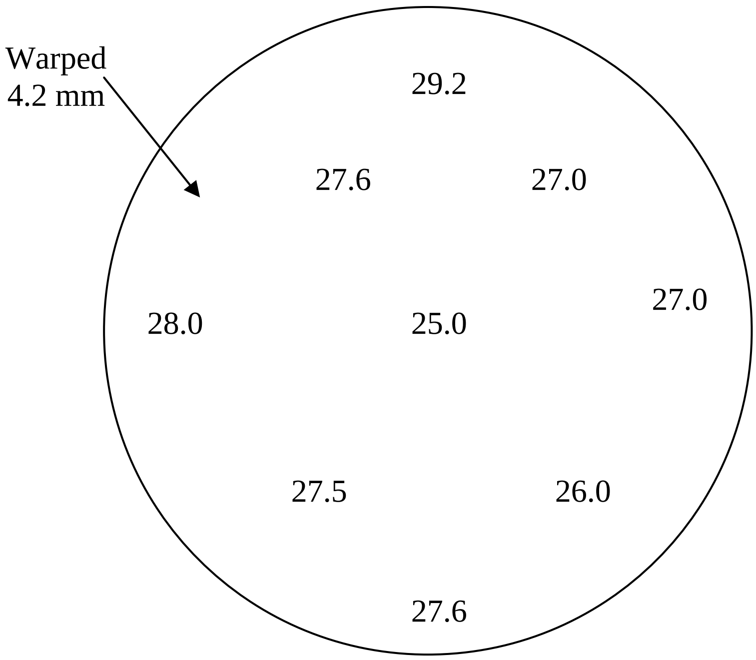
Pass	Height
1	45.3
	41.5
	46.7
Δh	**5.2**
2	44.3
	45.9
	42.5
Δh	**3.4**
3	46.0
	48.4
	47.5
Δh	**2.4**
4	44.5
	40.2
Δh	**4.3**
5	43.8
	45.8
Δh	**2.0**

Effect 3



	Height
	26.4
	31.8
	31.4
	32.0
	28.4
	28.6
	29.0
	31.0
	32.5
Δh	**6.1**

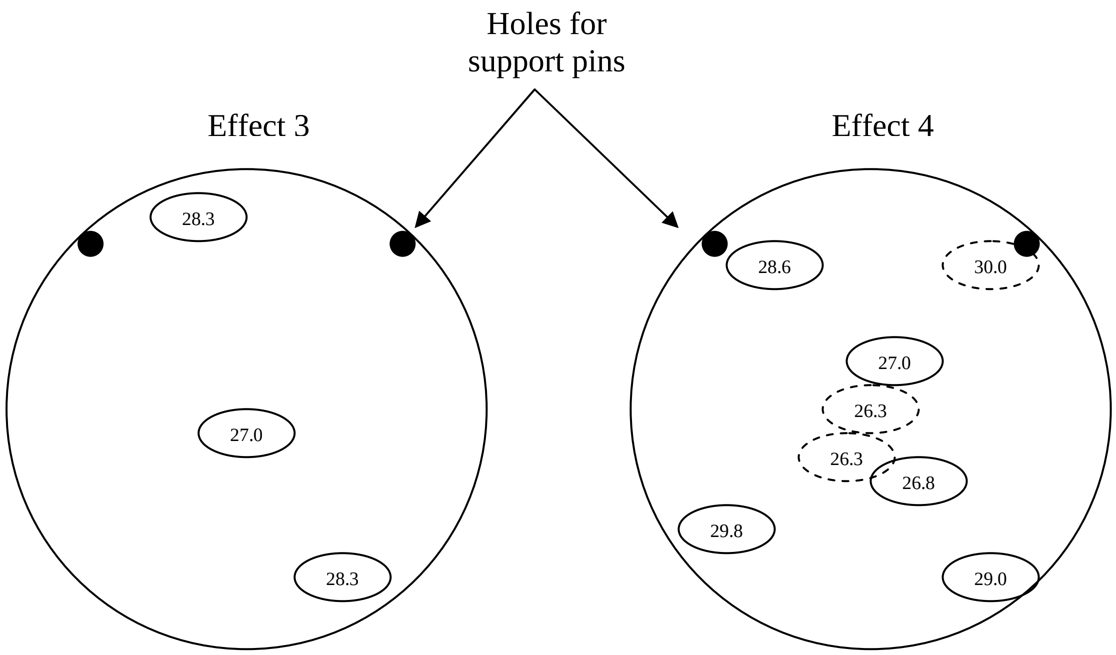
Effect 4



	Height
	29.2
	27.6
	28.0
	27.0
	25.0
	27.6
	27.0
	27.5
	26.0
Δh	**4.2**

A-6.4 Distribution plates at Edendale

ED2 Evaporator 3

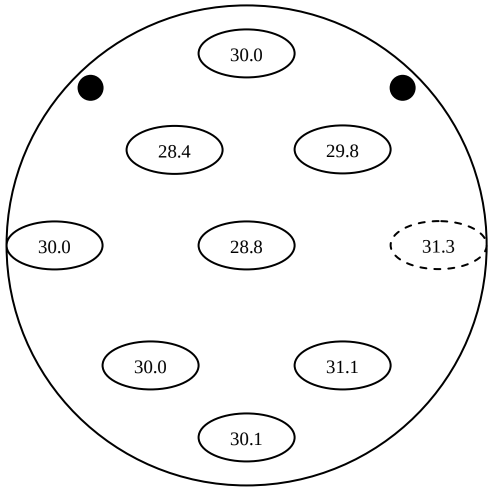


	Height	Alignment
	28.3	Ok.
	27.0	Sunk in middle
	28.3	
Δh	**1.3**	

	Height	Alignment
	28.6	Not tested.
	30.0	Sunk in middle.
	27.0	
	26.3	
	26.3	
	29.8	
	26.8	
	29.0	
Δh	**3.7**	

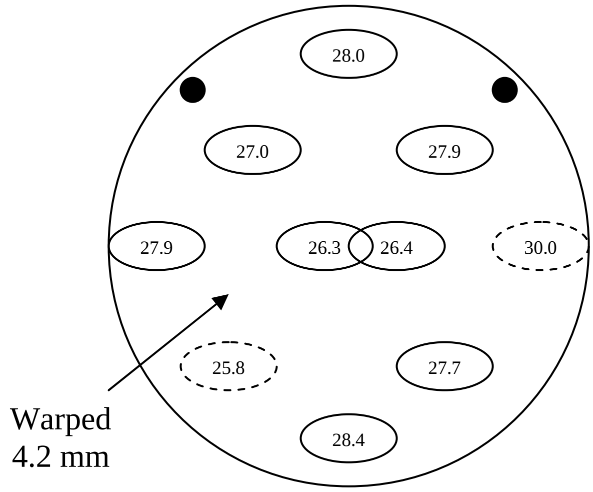
ED2 Evaporator 4

Effect 3



	Height
	30.0
	28.4
	29.8
	30.0
	28.8
	31.3
	30.0
	31.1
	30.1
Δh	**2.9**

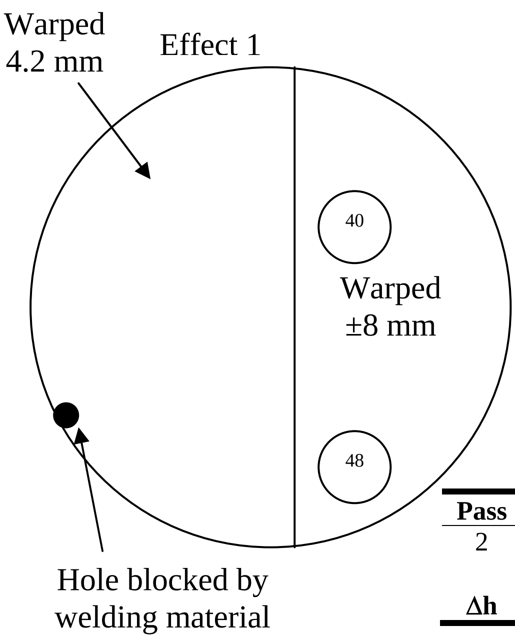
Effect 4



	Height
	28.0
	27.0
	27.9
	27.9
	26.3
	26.4
	30.0
	25.8
	27.7
	28.4
Δh	**4.2**

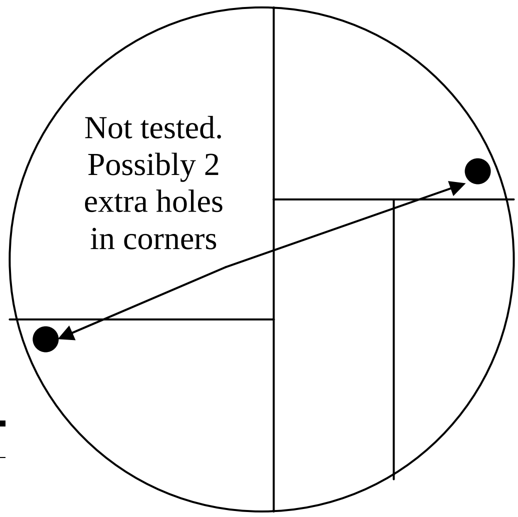
ED3 Evaporator 5

Effect 1



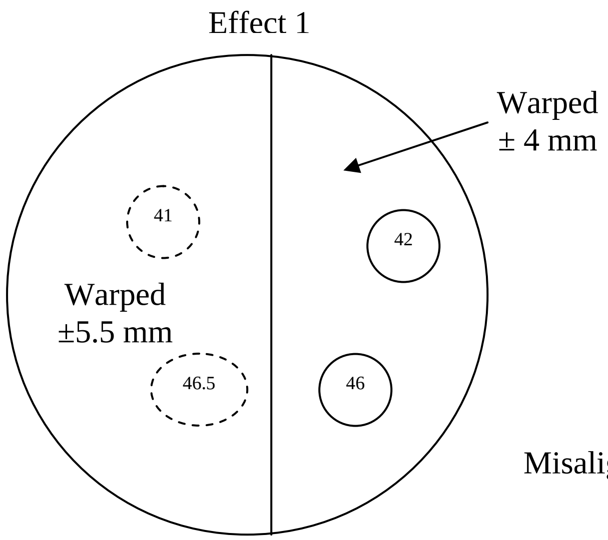
Pass	Height
2	40
	48
Δh	**8**

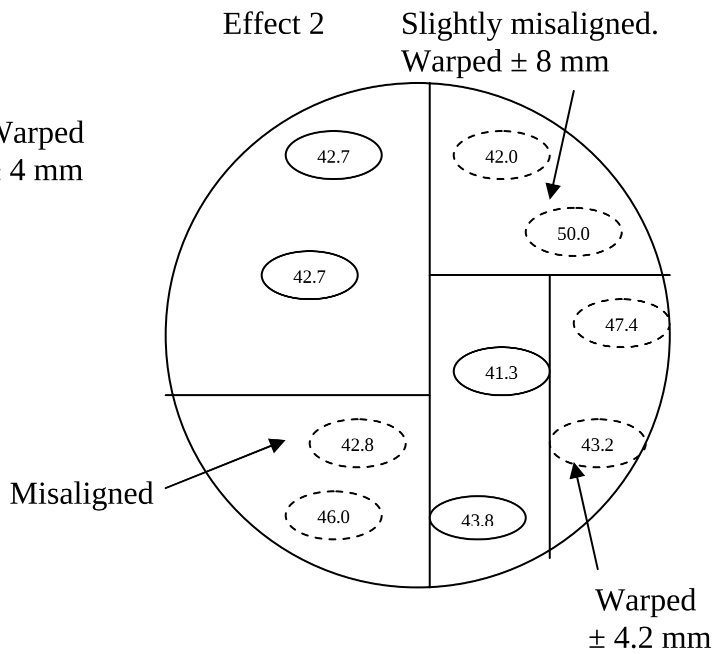
Effect 2



Effects 2, 3 and 4 were not tested

ED3 Evaporator 6





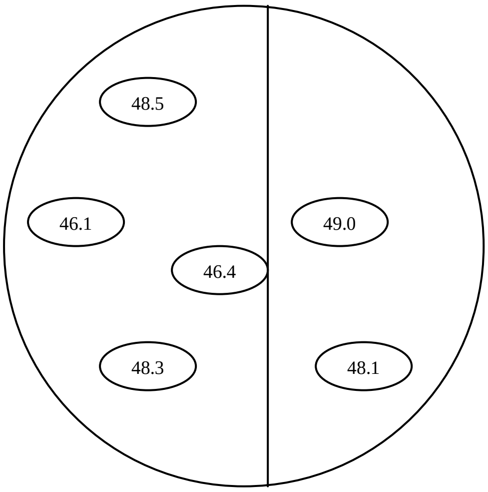
Pass	Height
1	41
	46.5
Δh	**5.5**
2	42
	46
Δh	**4**

Pass	Height
1	42.7
	42.7
Δh	**0.0**
2	42.0
	50.0
Δh	**8.0**
3	41.3
	43.8
Δh	**2.5**
4	47.4
	43.2
Δh	**4.2**
5	42.8
	46.0
Δh	**3.2**

Effects 3 and 4 were not tested.

ED3 Evaporator 7

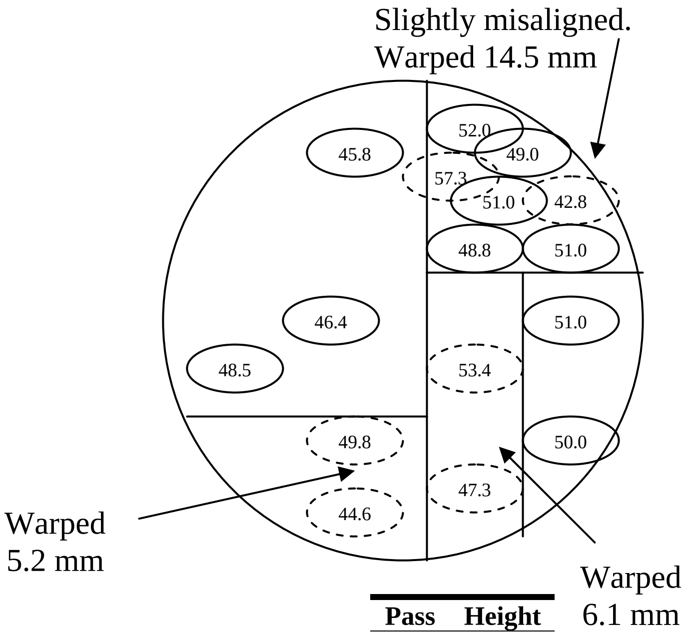
Effect 1



Pass	Height
1	48.5
	46.1
	46.4
	48.3
Δh	**2.4**
2	49.0
	48.1
Δh	**0.9**

Effects 3 and 4 were not tested for misalignment or warping.

Effect 2



Pass	Height
1	45.8
	46.4
	48.5
Δh	**2.7**
2	48.8
	52.0
	49.0
	57.3
	51.0
	42.8
	51.0
Δh	**14.5**
3	53.4
	47.3
Δh	**6.1**
4	51.0
	50.0
Δh	**1.0**
5	49.8
	44.6
Δh	**5.2**

A-7 Process data and spreadsheet sample calculations

This section gives example calculations for whole milk, skim milk and MPC-85 in Evaporator 4.

Most data came from Fonterra's process database on the Mercury network. Data was recorded at a rate of three of four times per minute. Microsoft Excel was used to calculate the average value for the data during the time period when total solids milk samples were being taken from the evaporators. The uncertainty was calculated as twice the standard deviation of the data during the time period.

The following calculations are for pass 1 of effect 1. Variables for the remaining passes were calculated in a similar fashion.

A-7.1 Whole milk on 23 April 2004, Evaporator 4

Total solids measurements

One or two total solids samples were tested for each pass. Concentrate samples were usually tested as duplicates because of their higher uncertainty.

- Inlet total solids = (13.10 ± 0.10) % TS
- Outlet total solids = (16.58 ± 0.10) % TS
- $\text{Average total solids in pass} = \frac{13.10 + 16.58}{2}\ \%\ \text{TS} = 14.84\%\ \text{TS}$
- $\text{Uncertainty} = \sqrt{0.10^2 + 0.10^2}\ \%\ \text{TS} = 0.14\ \%\ \text{TS}$

Effect & Pass	Measured Total Solids		Outlet Total Solids in pass		Average total solids in pass	
	% w/w	% w/w	% w/w	±	% w/w	±
Feed	13.10		13.10	0.10	-	
1-1	16.58		16.58	0.10	14.84	0.14
1-2	19.56		19.56	0.10	18.07	0.14
2-1	24.38		24.38	0.30	21.97	0.32
2-2	29.55		29.55	0.30	26.97	0.42
2-3	34.48		34.48	0.30	32.02	0.42
2-4	38.68		38.68	0.30	36.58	0.42
2-5	41.97		41.97	0.30	40.33	0.42
3-1	44.96	44.86	44.91	0.30	43.44	0.42
4-1	48.80	48.91	48.86	0.30	46.88	0.42

Temperatures

Most temperatures came from the process database. Feed temperatures came from operator logbooks.

- Feed temperature = 80ºC ± 0.5ºC
- Effect 1 temperature = 67.1ºC ± 0.10ºC
- Temperature difference = 80 – 67.1 = 12.9ºC
- $\text{Uncertainty} = \sqrt{0.50^2 + 0.10^2}\,^{\circ}\text{C} = 0.51\,^{\circ}\text{C}$

- Shell 1 temperature = 68.8ºC
- Effect 1 temperature = 67.1ºC
- Temperature difference for effect 1 = 1.7ºC
- Uncertainty = 2 standard deviation of (Shell 1 – Effect 1 temperature) = 0.4ºC

Effect	T_{shell} ºC	T_{effect} ºC	ΔT ºC	±
Feed		80	12.9	0.5
1	68.8	67.1	1.7	0.4
2	66.4	63.7	2.7	0.1
3	57.5	53.8	3.7	0.6
4	53.0	49.9	3.2	0.1

Flows

The density of whole milk at 10ºC was estimated at 1025 kg m^{-3} from Pisecky (1997). Sensors gave the densities of milk out of effects 2 and 4.

There were flowrate sensors for the milk entering and exiting the evaporators. The sensor for the cold milk entering the evaporators was much more accurate than the concentrate flow meter.

- Flow into pass 1 of effect 1 = (42.02 m^3 h^{-1}) (1025 kg m^{-3}) = 43065 kg h^{-1}.
- Uncertainty from sensors = 0.04 m^3 h^{-1}.

- $$\text{Flow out pass 1 of effect 1} = \frac{(13.10\%\ \text{TS})(43065\ \text{kg h}^{-1})}{16.58\%\ \text{TS}} = 34026\ \text{kg h}^{-1}$$
- $$\text{Uncertainty} = (34026\ \text{kg h}^{-1})\sqrt{\left(\frac{0.04}{42.02}\right)^2 + \left(\frac{0.10\ \%\text{TS}}{13.10\ \%\text{TS}}\right)^2 + \left(\frac{0.10\ \%\text{TS}}{16.58\ \%\text{TS}}\right)^2}$$
  $$= 333\ \text{kg h}^{-1}$$
- Evaporation = 43065 kg h^{-1} – 34026 kg h^{-1} = 9039 kg h^{-1}.
- $$\text{Uncertainty} = (9039\ \text{kg h}^{-1})\sqrt{\left(\frac{43\ \text{kg h}^{-1}}{43065\ \text{kg h}^{-1}}\right)^2 + \left(\frac{333\ \text{kg h}^{-1}}{34026\ \text{kg h}^{-1}}\right)^2}$$
  $$= 89\ \text{kg h}^{-1}$$

Effect & Pass	**Input Density**	**Measured flows**				**Flows out pass**		**Evaporation**	
	kg m^{-3}	**m^3 h^{-1}**	**±**	**kg h^{-1}**	**±**	**kg h^{-1}**	**±**	**kg h^{-1}**	**±**
Feed	1025	42.02	0.04	43065	43	43065	43	-	-
1-1						34026	333	9039	89
1-2						28842	267	5184	70
2-1						23140	336	5702	98
2-2						19092	243	4049	78
2-3						16362	190	2730	47
2-4						14585	159	1777	28
2-5	1090					13442	141	1143	17
3-1						12562	128	880	13
4-1	1124			9010	2065	11548	114	1014	14

Flashing

Flashing occurs when superheated milk enters an effect and evaporates to cool to the effect temperature.

- Surface area = π (0.04812 m) (615 tubes) (14 m) = 1302 m^2
- $$\text{Uncertainty} = (1302\ \text{m}^2)\sqrt{\left(\frac{0.0003\ \text{m}}{0.04812\ \text{m}}\right)^2} = 8.1\ \text{m}^2$$
- The ΔH_{vap} and Cp for milk were found for milk at the effect temperature.
- $$\text{Flash evaporation} = \frac{(43065\ \text{kg h}^{-1})(3883\ \text{J kg}^{-1}\text{K}^{-1})(80^\circ\text{C} - 67.1^\circ\text{C})}{2340889\ \text{J kg}^{-1}} = 925\ \text{kg h}^{-1}$$

- $$\text{Uncertainty} = \left(925\ \text{kg h}^{-1}\right)\sqrt{\left(\frac{43\ \text{kg h}^{-1}}{43065\ \text{kg h}^{-1}}\right)^2 + \left(\frac{0.51^{\circ}\text{C}}{80^{\circ}\text{C} - 67.1^{\circ}\text{C}}\right)^2}$$

  $$= 11\ \text{kg h}^{-1}$$

Effect & Pass	Number of tubes	Number of holes	Surface Area		ΔH_{vap}	Cp milk	Flashing	
			m^2	±	J kg^{-1}	J $kg^{-1}K^{-1}$	kg h^{-1}	±
1-1	615	658	1302	8	2340899	3883	925	11
1-2	483	523	1022	6	2340899			
2-1	320	360	677	4	2349291	3731	155	2
2-2	242	268	512	3	2349291			
2-3	219	250	463	3	2349291			
2-4	150	177	317	2	2349291			
2-5	114	134	241	2	2349291			
3-1	80	102	169	1	2373529	3204	179	3
4-1	96	121	203	1	2383018	3133	64	1

Heat Transfer Calculations

- Evaporation in tubes = 9039 kg h^{-1} – 925 kg h^{-1} = 8114 kg h^{-1}.
- $$\text{Uncertainty} = \sqrt{\left(11\ \text{kg h}^{-1}\right)^2 + \left(89\ \text{kg h}^{-1}\right)^2} = 100\ \text{kg h}^{-1}$$
- $$U = \frac{\Delta H_v\left(\dot{m}_{evap} - \dot{m}_{flash}\right)}{\left(\text{Surface Area}\right)\Delta T} = \frac{(2340889\ \text{J kg}^{-1})(8114\ \text{kg h}^{-1})}{\left(1302\ \text{m}^2\right)\left(1.7^{\circ}\text{C}\right)(3600\ \text{s h}^{-1})} = 2336\ \text{W m}^{-2}\text{K}^{-1}$$
- $$\text{Uncertainty} = \left(2336\ \text{W m}^{-2}\text{K}^{-1}\right)\sqrt{\left(\frac{100}{8114\ \text{kg h}^{-1}}\right)^2 + \left(\frac{8}{1302\ \text{m}^2}\right)^2\left(\frac{0.4}{1.7^{\circ}\text{C}}\right)^2}$$

  $$= 478\ \text{W m}^{-2}\text{K}^{-1}$$
- $$\text{Average outlet wetting rate} = \frac{34026\ \text{kg h}^{-1}}{\left(3600\ \text{s h}^{-1}\right)\pi\left(0.04812\ \text{m}\right)(615\ \text{tubes})}$$

  $$= 0.102\ \text{kg m}^{-1}\text{s}^{-1}$$
- $$\text{Uncertainty} = \left(0.102\ \text{kg m}^{-1}\text{s}^{-1}\right)\sqrt{\left(\frac{333\ \text{kg h}^{-1}}{34026\ \text{kg h}^{-1}}\right)^2 + \left(\frac{0.0003\ \text{m}}{0.04812\ \text{m}}\right)^2}$$

  $$= 0.002\ \text{kg m}^{-1}\text{s}^{-1}$$
- $$\text{Underfed tubes outlet wetting rate} = \frac{34026\ \text{kg h}^{-1}}{\left(3600\ \text{s h}^{-1}\right)\pi\left(0.04812\ \text{m}\right)(658\ \text{holes})}$$

  $$= 0.095\ \text{kg m}^{-1}\text{s}^{-1}$$

- $$\text{Uncertainty} = \left(0.095\ \text{kg m}^{-1}\text{s}^{-1}\right)\sqrt{\left(\frac{333\ \text{kg h}^{-1}}{34026\ \text{kg h}^{-1}}\right)^2 + \left(\frac{0.0003\ \text{m}}{0.04812\ \text{m}}\right)^2}$$
$$= 0.002\ \text{kg m}^{-1}\text{s}^{-1}$$

Effect & Pass	Evaporation in tubes		Overall Heat Transfer Coefficient, U		Average Outlet Wetting Rate		Outlet Wetting Rate for Underfed Tubes	
	kg h^{-1}	±	W m^{-1}K^{-1}	±	kg m^{-1}s^{-1}	±	kg m^{-1}s^{-1}	±
1-1	8114	100	2336	478	0.102	0.002	0.095	0.002
1-2	5184	70	1901	388	0.110	0.002	0.101	0.002
2-1	5547	100	1947	82	0.133	0.003	0.118	0.003
2-2	4049	78	1879	78	0.145	0.003	0.131	0.003
2-3	2730	47	1400	57	0.137	0.003	0.120	0.003
2-4	1777	28	1330	53	0.179	0.004	0.151	0.004
2-5	1143	17	1127	45	0.217	0.005	0.184	0.004
3-1	701	16	729	119	0.289	0.007	0.226	0.005
4-1	950	15	983	35	0.221	0.005	0.175	0.004

Vapour Properties

The vapour temperatures, pressures and densities were found at the effect temperature.

- $$\text{Outlet vapour velocity} = \frac{9039\ \text{kg h}^{-1}}{\left(3600\ \text{s h}^{-1}\right)\left(615\ \text{tubes}\right)\left(0.18\ \text{kg m}^{-3}\right)\left(\pi / 4\right)\left(0.04812^2\right)}$$
$$= 13\ \text{m s}^{-1}$$

Effect & Pass	Vapour temperature ºC	Vapour pressure Pa	Vapour density kg m^{-3}	Number of tubes -	Vapour velocity m s^{-1}
1-1	67.06	27415	0.18	615	13
1-2	67.06	27415	0.18	483	9
2-1	63.67	23567	0.15	320	18
2-2	63.67	23567	0.15	242	17
2-3	63.67	23567	0.15	219	12
2-4	63.67	23567	0.15	150	12
2-5	63.67	23567	0.15	114	10
3-1	53.79	14861	0.10	80	17
4-1	49.89	12277	0.08	96	20

A-7.2 Skim milk on 27 February 2004, Evaporator 4

Total solids measurements

The outlet total solids was the average of all values from the lab from a particular pass. The concentrate sample were sometimes tested as duplicates.

- Inlet total solids = (10.13 ± 0.10) % TS
- Outlet total solids = (13.34 ± 0.10) % TS
- $\text{Average total solids in pass} = \frac{10.13 + 13.34}{2}\ \%\ \text{TS} = 11.77\ \%\ \text{TS}$
- $\text{Uncertainty} = \sqrt{0.10^2 + 0.10^2}\ \%\ \text{TS} = 0.14\ \%\ \text{TS}$

Effect & Pass	Measured Total Solids		Outlet Total Solids in pass		Average total solids in pass	
	% w/w	% w/w	% w/w	±	% w/w	±
Feed	10.19		10.19	0.10	-	
1-1	13.34		13.34	0.10	11.77	0.14
1-2	17.12		17.12	0.10	15.23	0.14
2-1	21.87		21.87	0.30	19.50	0.32
2-2	27.14		27.14	0.30	24.51	0.42
2-3	32.84		32.84	0.30	29.99	0.42
2-4	37.54		37.54	0.30	35.19	0.42
2-5	41.35		41.35	0.30	39.45	0.42
3-1	44.70		44.70	0.30	43.03	0.42
4-1	49.21	49.22	49.22	0.30	46.96	0.42

Temperatures

Feed temperatures came from operator logbooks. The remaining temperatures came from the process database.

- Feed temperature: 86ºC
- Effect 1 temperature: 69.2ºC
- Temperature difference = 86 – 69.2 = 16.8ºC
- $\text{Uncertainty} = \sqrt{0.50^2 + 0.10^2}\ ^\circ\text{C} = 0.51\ ^\circ\text{C}$

- Shell 1 temperature = 72.3ºC

- Effect 1 temperature 69.2ºC
- Temperature difference for effect 1 = 3.1ºC
- Uncertainty = 2 * standard deviation of (Shell 1 – Effect 1 temperature)

  = 0.2ºC

Effect	$\mathbf{T_{shell}}$ **ºC**	$\mathbf{T_{effect}}$ **ºC**	**ΔT ºC**	**±**
Feed		86	16.8	0.5
1	72.3	69.2	3.1	0.2
2	68.6	65.0	3.6	0.2
3	60.3	56.7	3.6	0.2
4	55.7	50.0	5.7	0.3

Flows

The density of skim milk at 10ºC was estimated at 1040 kg m^{-3}, from Pisecky (1997).

- Flow into pass 1 of effect 1 = (60.52 m^3 h^{-1}) (1040 kg m^{-3}) = 62936 kg h^{-1}.
- Uncertainty from sensors was 0.13 m^3 h^{-1}.
- $\text{Flow out pass 1 of effect 1} = \frac{(10.19\%\ \text{TS})(62936\ \text{kg h}^{-1})}{13.34\ \%\ \text{TS}} = 48075\ \text{kg h}^{-1}$
- $\text{Uncertainty} = (48075\ \text{kg h}^{-1})\sqrt{\left(\frac{0.13}{60.52}\right)^2 + \left(\frac{0.10\ \%\text{TS}}{10.19\ \%\text{TS}}\right)^2 + \left(\frac{0.10\ \%\text{TS}}{13.34\ \%\text{TS}}\right)^2}$

  $= 602\ \text{kg h}^{-1}$
- Evaporation = 62936 kg h^{-1} – 48075 kg h^{-1} = 14861 kg h^{-1}.
- $\text{Uncertainty} = (14861\ \text{kg h}^{-1})\sqrt{\left(\frac{0.13\ \text{m}^3\ \text{h}^{-1}}{60.52\ \text{m}^3\ \text{h}^{-1}}\right)^2 + \left(\frac{602\ \text{kg h}^{-1}}{48075\ \text{kg h}^{-1}}\right)^2}$

  $= 189\ \text{kg h}^{-1}$

Effect & Pass	Input Density	Measured flows				Flows out pass		Evaporation	
	kg m^{-3}	m^3 h^{-1}	±	kg h^{-1}	±	kg h^{-1}	±	kg h^{-1}	±
Feed	1040	60.52	0.13	62936	132	62936	132	-	-
1-1						48075	602	14861	189
1-2	1055					37460	435	10615	181
2-1						29324	498	8136	167
2-2						23630	353	5694	129
2-3						19529	265	4101	83
2-4						17084	219	2445	46
2-5	1153					15510	192	1574	28
3-1						14347	173	1162	20
4-1	1208			9010	2065	13031	153	1316	22

Flashing

- Surface area = π (0.04812 m) (615 tubes) (14 m) = 1302 m^2
- $$\text{Uncertainty} = \left(1302\,\text{m}^2\right)\sqrt{\left(\frac{0.0003\,\text{m}}{0.04812\,\text{m}}\right)^2} = 8.1\,\text{m}^2$$
- The ΔH_{vap} and Cp for milk were found for milk at the effect temperature.
- $$\text{Flash evaporation} = \frac{\left(62396\,\text{kg h}^{-1}\right)\left(3952\,\text{J kg}^{-1}\text{K}^{-1}\right)\left(86^\circ\text{C} - 69.2^\circ\text{C}\right)}{2335511\,\text{J kg}^{-1}}$$
  $$= 1787\,\text{kg h}^{-1}$$
- $$\text{Uncertainty} = \left(1787\,\text{kg h}^{-1}\right)\sqrt{\left(\frac{0.13\,\text{m}^3\,\text{h}^{-1}}{62936\,\text{m}^3\,\text{h}^{-1}}\right)^2 + \left(\frac{0.51^\circ\text{C}}{86^\circ\text{C} - 69.2^\circ\text{C}}\right)^2}$$
  $$= 15\,\text{kg h}^{-1}$$

Effect & Pass	Number of tubes	Number of holes	Surface Area		ΔH_{vap}	Cp milk	Flashing	
			m^2	±	J kg^{-1}	J kg^{-1}K^{-1}	kg h^{-1}	±
1-1	615	658	1302	8	2335511	3952	1787	15
1-2	483	523	1022	6	2335511			
2-1	320	360	677	4	2345951	3789	255	3
2-2	242	268	512	3	2345951			
2-3	219	250	463	3	2345951			
2-4	150	177	317	2	2345951			
2-5	114	134	241	2	2345951			
3-1	80	102	169	1	2366376	3221	175	2
4-1	96	121	203	1	2382706	3138	127	2

Heat Transfer Calculations

- Evaporation in tubes = 14861 kg h^{-1} – 1787 kg h^{-1} = 13075 kg h^{-1}.
- $\text{Uncertainty} = \sqrt{\left(15\ \text{kg h}^{-1}\right)^2 + \left(189\ \text{kg h}^{-1}\right)^2} = 204\ \text{kg h}^{-1}$
- $U = \dfrac{\Delta H_v\left(\dot{m}_{evap} - \dot{m}_{flash}\right)}{(\text{Surface Area})\Delta T} = \dfrac{(2335511\ \text{J kg}^{-1})(13075\ \text{kg h}^{-1})}{\left(1302\ \text{m}^2\right)\left(3.1^\circ\text{C}\right)(3600\ \text{s h}^{-1})} = 2123\ \text{W m}^{-2}\text{K}^{-1}$
- $\text{Uncertainty} = \left(2123\ \text{W m}^{-2}\text{K}^{-1}\right)\sqrt{\left(\dfrac{204}{13075\ \text{kg h}^{-1}}\right)^2 + \left(\dfrac{8}{1302\ \text{m}^2}\right)^2 + \left(\dfrac{0.2}{3.1^\circ\text{C}}\right)^2}$

  $= 113\ \text{W m}^{-2}\text{K}^{-1}$

- $\text{Average outlet wetting rate} = \dfrac{48075\ \text{kg h}^{-1}}{\left(3600\ \text{s h}^{-1}\right)\pi\left(0.04812\ \text{m}\right)(615\ \text{tubes})}$

  $= 0.144\ \text{kg m}^{-1}\text{s}^{-1}$
- $\text{Uncertainty} = \left(0.144\ \text{kg m}^{-1}\text{s}^{-1}\right)\sqrt{\left(\dfrac{602\ \text{kg h}^{-1}}{48075\ \text{kg h}^{-1}}\right)^2 + \left(\dfrac{0.0003\ \text{m}}{0.04812\ \text{m}}\right)^2}$

  $= 0.003\ \text{kg m}^{-1}\text{s}^{-1}$
- $\text{Underfed tubes outlet wetting rate} = \dfrac{48075\ \text{kg h}^{-1}}{\left(3600\ \text{s h}^{-1}\right)\pi\left(0.04812\ \text{m}\right)(658\ \text{holes})}$

  $= 0.134\ \text{kg m}^{-1}\text{s}^{-1}$
- $\text{Uncertainty} = \left(0.134\ \text{kg m}^{-1}\text{s}^{-1}\right)\sqrt{\left(\dfrac{602\ \text{kg h}^{-1}}{48075\ \text{kg h}^{-1}}\right)^2 + \left(\dfrac{0.0003\ \text{m}}{0.04812\ \text{m}}\right)^2}$

  $= 0.003\ \text{kg m}^{-1}\text{s}^{-1}$

Effect & Pass	Evaporation in tubes		Overall Heat Transfer Coefficient, U		Average Outlet Wetting Rate		Outlet Wetting Rate for Underfed Tubes	
	kg h^{-1}	±	W $m^{-1}K^{-1}$	±	kg $m^{-1}s^{-1}$	±	kg $m^{-1}s^{-1}$	±
1-1	13075	204	2123	113	0.144	0.003	0.134	0.003
1-2	10615	181	2195	119	0.143	0.003	0.132	0.003
2-1	7882	171	2116	120	0.168	0.004	0.150	0.004
2-2	5694	129	2021	114	0.179	0.005	0.162	0.004
2-3	4101	83	1609	89	0.164	0.004	0.144	0.004
2-4	2445	46	1400	77	0.209	0.005	0.177	0.004
2-5	1574	28	1186	65	0.250	0.006	0.213	0.005
3-1	987	23	1067	60	0.330	0.008	0.258	0.006
4-1	1190	24	680	37	0.249	0.006	0.198	0.005

Vapour Properties

The vapour temperatures, pressures and densities were found at the effect temperature.

- $\text{Outlet vapour velocity} = \dfrac{14861\,\text{kg h}^{-1}}{\left(3600\,\text{s h}^{-1}\right)\left(615\,\text{tubes}\right)\left(0.19\,\text{kg m}^{-3}\right)\left(\pi/4\right)\left(0.04812^{2}\right)}$

  $= 13\,\text{m s}^{-1}$

Effect & Pass	Vapour temperature °C	Vapour pressure Pa	Vapour density $kg\ m^{-3}$	Number of tubes -	Vapour velocity $m\ s^{-1}$
1-1	69.22	30146	0.19	615	19
1-2	69.22	30146	0.19	483	17
2-1	65.02	25041	0.16	320	24
2-2	65.02	25041	0.16	242	22
2-3	65.02	25041	0.16	219	18
2-4	65.02	25041	0.16	150	15
2-5	65.02	25041	0.16	114	13
3-1	56.72	17094	0.11	80	20
4-1	50.02	12356	0.08	96	25

A-7.3 MPC-85 on 17 March 2004, Evaporator 4

Total solids measurements

The outlet total solids is the average of all tests from the lab from a particular pass. The concentrate sample were sometimes tested as duplicates. This run was under 4-effect mode. The evaporators now process MPCs under 3-effect mode, which has similar calculations.

- Inlet total solids: (8.94 ± 0.10) % TS
- Outlet total solids: (11.60 ± 0.10) % TS
- $\text{Average total solids in pass} = \dfrac{8.94 + 11.60}{2}\,\%\,\text{TS} = 10.27\,\%\,\text{TS}$
- $\text{Uncertainty} = \sqrt{0.10^{2} + 0.10^{2}}\,\%\,\text{TS} = 0.14\,\%\,\text{TS}$

Effect & Pass	Input Total Solids		Outlet Total Solids		Average total solids in pass	
	% w/w	% w/w	% w/w	±	% w/w	±
Feed	8.94		8.94	0.20	-	
1-1	11.60		11.60	0.20	10.27	0.28
1-2	14.45	14.51	14.48	0.20	13.04	0.28
2-1	17.48		17.48	0.20	15.98	0.28
2-2	20.57		20.57	0.20	19.03	0.28
2-3	22.33		22.33	0.20	21.45	0.28
2-4	22.34		22.34	0.20	22.34	0.28
2-5	22.19	21.86	22.03	0.20	22.18	0.28
3-1	23.06	23.16	23.11	0.20	22.57	0.28
4-1	24.63	24.64	24.64	0.20	23.87	0.28

Temperatures

- Feed temperatures came from operator logbooks. The remaining temperatures came from the process database.
- Feed temperature = 86ºC
- Effect 1 temperature = 65.5ºC
- Temperature difference = 86 – 65.5 = 20.5ºC
- $\text{Uncertainty} = \sqrt{0.50^2 + 0.10^2}\,^\circ\text{C} = 0.51^\circ\text{C}$

- Shell 1 temperature = 67.5ºC
- Effect 1 temperature 65.5ºC
- Temperature difference for effect 1 = 2.0ºC
- Uncertainty = 2 * STDEV (Shell 1 temperature – Effect 1 temperature) = 0.2ºC

Effect	T_{shell} ºC	T_{effect} ºC	ΔT ºC	±
Feed		86	20.5	0.5
1	67.5	65.5	2.0	0.2
2	67.5	65.5	2.0	0.2
3	54.8	52.2	2.6	0.2
4	52.1	50.0	2.1	0.2

Flows

The density of MPC-85 at 10ºC was estimated at 1027 kg m^{-3}, from Pisecky (1997).

Sensors gave the densities of milk out of effects 2 and 4. There were flowrate sensors for the milk entering and exiting the evaporators. The sensor for the cold milk entering the evaporators was the most accurate.

- Flow into pass 1 of effect 1 = (38.00 m^3 h^{-1}) (1027 kg m^{-3}) = 39023 kg h^{-1}.
- Uncertainty from sensors was 0.09 m^3 h^{-1}.
- $\text{Flow out pass 1 of effect 1} = \dfrac{(8.94\,\%\,\text{TS})(39023\,\text{kg h}^{-1})}{11.60\,\%\,\text{TS}} = 30075\,\text{kg h}^{-1}$
- $$\text{Uncertainty} = (30075\,\text{kg h}^{-1})\sqrt{\left(\frac{0.09\,\text{m}^3\,\text{h}^{-1}}{38.00\,\text{m}^3\,\text{h}^{-1}}\right)^2 + \left(\frac{0.10\,\%\text{TS}}{8.94\,\%\text{TS}}\right)^2 + \left(\frac{0.10\,\%\text{TS}}{11.60\,\%\text{TS}}\right)^2}$$
  $$= 431\,\text{kg h}^{-1}$$

- Evaporation = 39023 kg h^{-1} – 30075 kg h^{-1} = 8948 kg h^{-1}.
- $$\text{Uncertainty} = (8948\,\text{kg h}^{-1})\sqrt{\left(\frac{0.09\,\text{m}^3\,\text{h}^{-1}}{38.00\,\text{m}^3\,\text{h}^{-1}}\right)^2 + \left(\frac{431\,\text{kg h}^{-1}}{30075\,\text{kg h}^{-1}}\right)^2}$$
  $$= 130\,\text{kg h}^{-1}$$

Effect & Pass	Input Density kg m^{-3}	Measured flows m^3 h^{-1}	±	kg h^{-1}	±	Flows out pass kg h^{-1}	±	Evaporation kg h^{-1}	±
Feed	1027	38.00	0.09	39023	92	39023	92	-	
1-1						30075	431	8948	130
1-2	1034					24093	322	5982	117
2-1						19958	255	4135	76
2-2						16960	314	2998	67
2-3						15623	276	1337	34
2-4						15616	275	7	0
2-5	1050					15840	282	-223	-6
3-1						15096	261	744	18
4-1	1069			9010	2065	14161	237	934	22

Flashing

- Surface area = π (0.04812 m) (615 tubes) (14 m) = 1302 m^2
- $$\text{Uncertainty} = \left(1302\ \text{m}^2\right)\sqrt{\left(\frac{0.0003\ \text{m}}{0.04812\ \text{m}}\right)^2} = 8.1\ \text{m}^2$$
- The ΔH_{vap} and Cp for milk were found for milk at the effect temperature.
- $$\text{Flash evaporation} = \frac{\left(39023\ \text{kg h}^{-1}\right)\left(3979\ \text{J kg}^{-1}\text{K}^{-1}\right)\left(86^\circ\text{C} - 65.5^\circ\text{C}\right)}{2344755\ \text{J kg}^{-1}}$$
  $$= 1026\ \text{kg h}^{-1}$$
- $$\text{Uncertainty} = \left(1026\ \text{kg h}^{-1}\right)\sqrt{\left(\frac{0.09\ \text{m}^3\ \text{h}^{-1}}{38.00\ \text{m}^3\ \text{h}^{-1}}\right)^2 + \left(\frac{0.51^\circ\text{C}}{86^\circ\text{C} - 65.5^\circ\text{C}}\right)^2}$$
  $$= 9\ \text{kg h}^{-1}$$

Effect & Pass	Number of tubes	Number of holes	Surface Area		ΔH_{vap}	Cp milk	Flashing	
			m^2	±	J kg^{-1}	J $kg^{-1}K^{-1}$	kg h^{-1}	±
1-1	615	658	1302	8	2344755	3979	1026	9
1-2	483	523	1022	6	2344755			
2-1	320	360	677	4	2352306	3849	120	2
2-2	242	268	512	3	2352306			
2-3	219	250	463	3	2352306			
2-4	150	177	317	2	2352306			
2-5	114	134	241	2	2352306			
3-1	80	102	169	1	2377304	3668	249	5
4-1	96	121	203	1	2382760	3642	52	1

Heat Transfer Calculations

- Evaporation in tubes = 8948 kg h^{-1} – 1026 kg h^{-1} = 7922 kg h^{-1}.
- $$\text{Uncertainty} = \sqrt{\left(9\ \text{kg h}^{-1}\right)^2 + \left(130\ \text{kg h}^{-1}\right)^2} = 139\ \text{kg h}^{-1}$$
- $$U = \frac{\Delta H_v\left(\dot{m}_{evap} - \dot{m}_{flash}\right)}{\left(\text{Surface Area}\right)\Delta T} = \frac{\left(23447551\ \text{J kg}^{-1}\right)\left(7922\ \text{kg h}^{-1}\right)}{\left(1302\ \text{m}^2\right)\left(2.0^\circ\text{C}\right)\left(3600\ \text{s h}^{-1}\right)} = 1976\ \text{W m}^{-2}\text{K}^{-1}$$
- $$\text{Uncertainty} = \left(1976\ \text{W m}^{-2}\text{K}^{-1}\right)\sqrt{\left(\frac{139}{7922\ \text{kg h}^{-1}}\right)^2 + \left(\frac{8}{1302\ \text{m}^2}\right)^2 + \left(\frac{0.2}{2.0^\circ\text{C}}\right)^2}$$
  $$= 174\ \text{W m}^{-2}\text{K}^{-1}$$

- $$\text{Average outlet wetting rate} = \frac{30075\ \text{kg h}^{-1}}{\left(3600\ \text{s h}^{-1}\right)\pi\left(0.04812\ \text{m}\right)\left(615\ \text{tubes}\right)}$$

  $$= 0.090\ \text{kg m}^{-1}\text{s}^{-1}$$

- $$\text{Uncertainty} = \left(0.090\ \text{kg m}^{-1}\text{s}^{-1}\right)\sqrt{\left(\frac{431\ \text{kg h}^{-1}}{30075\ \text{kg h}^{-1}}\right)^2 + \left(\frac{0.0003\ \text{m}}{0.04812\ \text{m}}\right)^2}$$

  $$= 0.002\ \text{kg m}^{-1}\text{s}^{-1}$$

- $$\text{Underfed tubes outlet wetting rate} = \frac{30075\ \text{kg h}^{-1}}{\left(3600\ \text{s h}^{-1}\right)\pi\left(0.04812\ \text{m}\right)\left(658\ \text{holes}\right)}$$

  $$= 0.084\ \text{kg m}^{-1}\text{s}^{-1}$$

- $$\text{Uncertainty} = \left(0.084\ \text{kg m}^{-1}\text{s}^{-1}\right)\sqrt{\left(\frac{431\ \text{kg h}^{-1}}{30075\ \text{kg h}^{-1}}\right)^2 + \left(\frac{0.0003\ \text{m}}{0.04812\ \text{m}}\right)^2}$$

  $$= 0.002\ \text{kg m}^{-1}\text{s}^{-1}$$

Effect & Pass	**Evaporation in tubes**		**Overall Heat Transfer Coefficient, U**		**Average Outlet Wetting Rate**		**Outlet Wetting Rate for Underfed Tubes**	
	kg h^{-1}	±	**W m^{-1}K^{-1}**	±	**kg m^{-1}s^{-1}**	±	**kg m^{-1}s^{-1}**	±
1-1	7922	139	1976	174	0.090	0.002	0.084	0.002
1-2	5982	117	1900	169	0.092	0.002	0.085	0.002
2-1	4015	78	1469	163	0.115	0.003	0.102	0.002
2-2	2998	67	1451	162	0.129	0.004	0.116	0.003
2-3	1337	34	715	80	0.131	0.004	0.115	0.003
2-4	7	0	5	1	0.191	0.005	0.162	0.004
2-5	-223	-6	-229	-26	0.255	0.007	0.217	0.006
3-1	494	23	743	64	0.347	0.009	0.272	0.007
4-1	883	23	1356	141	0.271	0.007	0.215	0.006

Vapour Properties

The vapour temperatures, pressures and densities were found at the effect temperature.

- $$\text{Outlet vapour velocity} = \frac{8948\ \text{kg h}^{-1}}{\left(3600\ \text{s h}^{-1}\right)\left(615\ \text{tubes}\right)\left(0.16\ \text{kg m}^{-3}\right)\left(\pi/4\right)\left(0.04812^2\right)}$$

  $$= 13\ \text{m s}^{-1}$$

Effect & Pass	Vapour temperature ºC	Vapour pressure Pa	Vapour density kg m^{-3}	Number of tubes -	Vapour velocity m s^{-1}
1-1	65.50	25587	0.16	615	13
1-2	65.50	25587	0.16	483	11
2-1	62.44	22298	0.14	320	14
2-2	62.44	22298	0.14	242	13
2-3	62.44	22298	0.14	219	6
2-4	62.44	22298	0.14	150	0
2-5	62.44	22298	0.14	114	-2
3-1	52.24	13784	0.09	80	15
4-1	50.00	12342	0.08	96	18

A-8. Fonterra Clandeboye's total solids procedure

The total solids method is based on the standard specified by the International Dairy Federation, which is found in:

IDF Standard 21B: 1987. *Milk, cream and evaporated milk. Determination of Total Solids Content (Reference Method).* International Dairy Federation, Brussels.

The procedure defines milk as having total solids below approximately 20% TS (mass fraction of 0.20) and milk concentrate as having 20% TS or more total solids content. This applies for skim and whole milks, MPC-70 and MPC-85.

The quantities used were 3 g of milk or 1 g of milk concentrate. Milk concentrate was thinned by diluting with approximately 2 mL distilled water for testing. The milk was dried at 105ºC for 2 hours, followed by 1 hour cooling to room temperature in a desiccator. The samples were weighed. Results between duplicate samples had to agree to within a total solids content of 0.10% TS (0.001 weight fraction) for milks and 0.30% TS for concentrated milks and MPCs.

In practice, milks had excellent repeatability. Skim and whole milk concentrates at 50% TS had uncertainties up to ± 1% TS. MPC-85 above 20% TS had similar uncertainties.

A-9. Sensitivity analysis

A sensitivity analysis showed the susceptibility of the heat transfer coefficients, wetting rates and evaporation rates to variation in process data. The equations are listed below, followed by the derivations required to find the uncertainties in the variables.

The following pages show the variables and their uncertainties in Evaporators 1 and 4, while processing skim and whole milks, and MPC-85.

The results are reported in order of calculation: flashing, evaporation, overall heat transfer coefficient and wetting rates.

A-9.1 Equations for variables

- $\dot{m}_{flash} = \dot{m}\left(\frac{TS_{feed}}{TS_{pass\ n}}\right)\left(Cp_{milk}\right)\left(T_{effect\ of\ pass\ n} - T_{effect\ of\ pass\ n+1}\right)$

- $\dot{m}_{evap} = \dot{m}\frac{TS_{feed}}{TS_{pass\ n}} - \dot{m}\frac{TS_{feed}}{TS_{pass\ n+1}} \quad \Rightarrow \quad \dot{m}_{evap} = \dot{m}\,TS_{feed}\left(\frac{1}{TS_{pass\ n}} - \frac{1}{TS_{pass\ n+1}}\right)$

- $U = \frac{\Delta H\left(\dot{m}_{evap} - \dot{m}_{flash}\right)}{\pi\, d_i\, L\,(T_{shell} - T_{effect})\, n_{tubes}}$

- $\Gamma_{out} = \frac{\dot{m}\left(TS_{feed}/TS_{out}\right)}{\pi\, d_i\, n_{tubes}}$

The uncertainties for the variables are described below:

- ‘ΔFlashing’ is the uncertainty in flashing.

- ‘ΔEvaporation’ is the uncertainty in evaporation.

- ‘ΔOverall heat transfer coefficient’ is the uncertainty in the overall heat transfer coefficient.

- ‘ΔOutlet wetting rate’ is the uncertainty in the outlet wetting rate

A-9.2 Derived equations for sensitivity analysis

Explanation

The following terms show the equations derived for the sensitivity analysis. An example of a calculated variable is shown below.

- $\dot{m}_{evap} = \dot{m}\, TS_{feed}\left(\frac{1}{TS_{pass\,n}} - \frac{1}{TS_{pass\,n+1}}\right)$
- $\frac{\partial Evaporation}{\partial(\dot{m})} = TS_{feed}\left(\frac{1}{TS_{pass\,n}} - \frac{1}{TS_{pass\,n+1}}\right)$
- $\Delta(\dot{m})$ = the uncertainty in the recorded $\dot{m}$

Equations

- $$\Delta Flashing = \left|\frac{\partial Flashing}{\partial(\dot{m})}\right|\Delta(\dot{m}) + \left|\frac{\partial Flashing}{\partial(TS_{feed})}\right|\Delta(TS_{feed}) + \left|\frac{\partial Flashing}{\partial(TS_{pass\,n})}\right|\Delta(TS_{pass\,n})$$
$$+ \left|\frac{\partial Flashing}{\partial(TS_{effect\,of\,pass\,n} - TS_{effect\,of\,pass\,n+1})}\right|\Delta(TS_{effect\,of\,pass\,n} - TS_{effect\,of\,pass\,n+1})$$
$$+ \left|\frac{\partial Flashing}{\partial(Cp_{milk})}\right|\Delta(Cp_{milk})$$

- $$\Delta Evaporation = \left|\frac{\partial Evaporation}{\partial(\dot{m})}\right|\Delta(\dot{m}) + \left|\frac{\partial Evaporation}{\partial(TS_{feed})}\right|\Delta(TS_{feed})$$
$$+ \left|\frac{\partial Evaporation}{\partial\left(\frac{1}{TS_{pass\,n}} - \frac{1}{TS_{pass\,n+1}}\right)}\right|\Delta\left(\frac{1}{TS_{pass\,n}} - \frac{1}{TS_{pass\,n+1}}\right)$$

- $$\Delta U = \left|\frac{\partial U}{\partial(\Delta H)}\right|\Delta(\Delta H) + \left|\frac{\partial U}{\partial(Evaporation)}\right|\Delta(Evaporation) + \left|\frac{\partial U}{\partial(Flashing)}\right|\Delta(Flashing)$$
$$+ \left|\frac{\partial U}{\partial(L)}\right|\Delta(L) + \left|\frac{\partial U}{\partial(T_{shell} - T_{effect})}\right|\Delta(T_{shell} - T_{effect}) + 2\left|\frac{\partial U}{\partial(d_i)}\right|\Delta(d_i)$$

- $$\Delta\Gamma_{out\,of\,pass\,n} = \left|\frac{\partial\Gamma_{out\,of\,pass\,n}}{\partial(\dot{m})}\right|\Delta(\dot{m}) + \left|\frac{\partial\Gamma_{out\,of\,pass\,n}}{\partial(TS_{feed})}\right|\Delta(TS_{feed})$$
$$+ \left|\frac{\partial\Gamma_{out\,of\,pass\,n}}{\partial(TS_{pass\,n})}\right|\Delta TS_{pass\,n} + \left|\frac{\partial\Gamma_{out\,of\,pass\,n}}{\partial(d_i)}\right|\Delta(d_i)$$

A-9.3 Results

Δ Flashing

Skim Milk – Evaporator 1

Effect	Flashing kg s^{-1}	Term 1	Term 2	Term 3	Term 4	Term 5	Sum Terms	Uncertainty ± %
1	0.41	0.0037	0.0042	0.0042	0.0000	0.0497	0.062	15%
2	0.07	0.0007	0.0007	0.0005	0.0000	0.0257	0.028	38%
3	0.04	0.0004	0.0004	0.0002	0.0000	0.0092	0.010	25%
4	0.05	0.0005	0.0005	0.0002	0.0000	0.0084	0.010	18%

Skim Milk – Evaporator 4

Effect	Flashing kg s^{-1}	Term 1	Term 2	Term 3	Term 4	Term 5	Sum Terms	Uncertainty ± %
1	0.50	0.0010	0.0049	0.0049	0.0000	0.0342	0.045	9%
2	0.07	0.0001	0.0007	0.0004	0.0000	0.0057	0.007	10%
3	0.05	0.0001	0.0005	0.0002	0.0000	0.0022	0.003	6%
4	0.04	0.0001	0.0003	0.0002	0.0000	0.0024	0.003	9%

Whole Milk – Evaporator 1

Effect	Flashing kg s^{-1}	Term 1	Term 2	Term 3	Term 4	Term 5	Sum Terms	Uncertainty ± %
1	0.27	0.0023	0.0020	0.0020	0.0000	0.0321	0.038	14%
2	0.04	0.0004	0.0003	0.0002	0.0000	0.0151	0.016	37%
3	0.05	0.0004	0.0003	0.0002	0.0000	0.0066	0.008	16%
4	0.04	0.0003	0.0003	0.0002	0.0000	0.0064	0.007	18%

Whole Milk – Evaporator 4

Effect	Flashing kg s^{-1}	Term 1	Term 2	Term 3	Term 4	Term 5	Sum Terms	Uncertainty ± %
1	0.26	0.0003	0.0020	0.0020	0.0000	0.0269	0.031	12%
2	0.04	0.0000	0.0003	0.0002	0.0000	0.0058	0.006	15%
3	0.05	0.0001	0.0004	0.0002	0.0000	0.0036	0.004	9%
4	0.02	0.0000	0.0001	0.0001	0.0000	0.0032	0.003	19%

MPC-85 – Evaporator 4

Effect	Flashing kg s^{-1}	Term 1	Term 2	Term 3	Term 4	Term 5	Sum Terms	Uncertainty ± %
1	0.29	0.0007	0.0032	0.0032	0.0000	0.0216	0.029	10%
2	0.03	0.0001	0.0004	0.0002	0.0000	0.0051	0.006	17%
3	0.07	0.0002	0.0008	0.0006	0.0000	0.0034	0.005	7%
4	0.01	0.0000	0.0002	0.0001	0.0000	0.0027	0.003	21%

Δ Evaporation

Skim Milk – Evaporator 1

Effect - Pass	Evaporation kg s^{-1}	Term 1	Term 2	Term 3	Sum Terms	Uncertainty ± %
1-1	4.1	0.0372	0.0417	0.0735	0.152	4%
1-2	2.6	0.0235	0.0263	0.0364	0.086	3%
2-1	2.6	0.0237	0.0266	0.0412	0.092	4%
2-2	1.9	0.0175	0.0196	0.0322	0.069	4%
2-3	1.1	0.0098	0.0110	0.0143	0.035	3%
2-4	0.7	0.0062	0.0069	0.0076	0.021	3%
2-5	0.3	0.0029	0.0032	0.0032	0.009	3%
3	0.4	0.0032	0.0036	0.0033	0.010	3%
4	0.4	0.0032	0.0036	0.0030	0.010	3%

Skim Milk – Evaporator 4

Effect - Pass	Evaporation kg s^{-1}	Term 1	Term 2	Term 3	Sum Terms	Uncertainty ± %
1-1	4.1	0.0087	0.0405	0.0715	0.121	3%
1-2	2.9	0.0062	0.0289	0.0393	0.074	3%
2-1	2.3	0.0047	0.0222	0.0339	0.061	3%
2-2	1.6	0.0033	0.0155	0.0261	0.045	3%
2-3	1.1	0.0024	0.0112	0.0153	0.029	3%
2-4	0.7	0.0014	0.0067	0.0078	0.016	2%
2-5	0.4	0.0009	0.0043	0.0044	0.010	2%
3	0.3	0.0007	0.0032	0.0030	0.007	2%
4	0.4	0.0008	0.0036	0.0031	0.007	2%

Whole Milk – Evaporator 1

Effect - Pass	Evaporation kg s^{-1}	Term 1	Term 2	Term 3	Sum Terms	Uncertainty ± %
1-1	2.5	0.0210	0.0184	0.0330	0.072	3%
1-2	1.5	0.0121	0.0107	0.0156	0.038	3%
2-1	1.6	0.0137	0.0121	0.0209	0.047	3%
2-2	1.1	0.0091	0.0080	0.0156	0.033	3%
2-3	0.7	0.0058	0.0051	0.0084	0.019	3%
2-4	0.4	0.0034	0.0030	0.0044	0.011	3%
2-5	0.3	0.0027	0.0024	0.0032	0.008	3%
3	0.3	0.0028	0.0025	0.0030	0.008	2%
4	0.3	0.0028	0.0025	0.0028	0.008	2%

Whole Milk – Evaporator 4

Effect - Pass	Evaporation kg s^{-1}	Term 1	2	3	Sum Terms	Uncertainty ± %
1-1	2.5	0.0025	0.0192	0.0343	0.056	2%
1-2	1.4	0.0015	0.0110	0.0160	0.028	2%
2-1	1.6	0.0016	0.0121	0.0211	0.035	2%
2-2	1.1	0.0011	0.0086	0.0168	0.027	2%
2-3	0.8	0.0008	0.0058	0.0095	0.016	2%
2-4	0.5	0.0005	0.0038	0.0054	0.010	2%
2-5	0.3	0.0003	0.0024	0.0032	0.006	2%
3	0.2	0.0002	0.0019	0.0023	0.004	2%
4	0.3	0.0003	0.0022	0.0024	0.005	2%

MPC-85 – Evaporator 4

Effect - Pass	Evaporation kg s^{-1}	Term 1	2	3	Sum Terms	Uncertainty ± %
1-1	2.5	0.0059	0.0278	0.0492	0.083	3%
1-2	1.7	0.0039	0.0186	0.0258	0.048	3%
2-1	1.1	0.0027	0.0128	0.0211	0.037	3%
2-2	0.8	0.0020	0.0093	0.0176	0.029	3%
2-3	0.4	0.0009	0.0042	0.0069	0.012	3%
2-4	0.0	0.0000	0.0000	0.0000	0.000	3%
2-5	-0.1	-0.0001	-0.0007	-0.0011	-0.002	3%
3	0.2	0.0005	0.0023	0.0037	0.006	3%
4	0.3	0.0006	0.0029	0.0044	0.008	3%

∆ Overall heat transfer coefficients (OHTC)

Skim Milk – Evaporator 1

Effect - Pass	OHTC W $m^{-2}K^{-1}$	Term 1	2	3	4	5	6	Sum Terms	Uncertainty ± %
1-1	2544	0	106	43	0	677	47	826	32%
1-2	2274	0	76	55	0	509	35	640	28%
2-1	2836	0	103	31	0	724	52	857	30%
2-2	2844	0	103	41	0	699	50	842	30%
2-3	1763	0	57	45	0	420	30	523	30%
2-4	1620	0	49	66	0	370	27	485	30%
2-5	998	0	29	87	0	197	14	313	31%
3	960	0	31	31	0	182	18	244	25%
4	348	0	11	11	0	29	6	52	15%

Skim Milk – Evaporator 4

Effect - Pass	OHTC W $m^{-2}K^{-1}$	Term 1	2	3	4	5	6	Sum Terms	Uncertainty ± %
1-1	2123	0	71	26	0	108	39	205	10%
1-2	2195	0	55	33	0	93	33	182	8%
2-1	2116	0	59	7	0	108	39	174	8%
2-2	2021	0	57	9	0	99	36	165	8%
2-3	1609	0	41	10	0	77	28	128	8%
2-4	1400	0	33	14	0	64	23	111	8%
2-5	1186	0	26	19	0	51	18	96	8%
3	1067	0	27	12	0	55	20	93	9%
4	680	0	15	6	0	33	12	54	8%

Whole Milk – Evaporator 1

Effect - Pass	OHTC W $m^{-2}K^{-1}$	Term 1	2	3	4	5	6	Sum Terms	Uncertainty ± %
1-1	2046	0	66	35	0	641	37	742	36%
1-2	1689	0	45	45	0	430	25	519	31%
2-1	2235	0	65	22	0	517	41	604	27%
2-2	2019	0	60	29	0	448	36	538	27%
2-3	1417	0	39	33	0	307	25	379	27%
2-4	1225	0	32	48	0	253	20	333	27%
2-5	1277	0	33	63	0	256	20	351	28%
3	1091	0	31	28	0	208	20	267	24%
4	510	0	14	13	0	54	9	80	16%

Whole Milk – Evaporator 4

Effect - Pass	OHTC W $m^{-2}K^{-1}$	Term 1	2	3	4	5	6	Sum Terms	Uncertainty ± %
1-1	2336	0	58	32	0	476	43	567	24%
1-2	1901	0	38	41	0	318	29	397	21%
2-1	1947	0	44	8	0	70	36	122	6%
2-2	1879	0	44	11	0	65	33	120	6%
2-3	1400	0	30	12	0	48	24	89	6%
2-4	1330	0	26	17	0	44	22	87	7%
2-5	1127	0	21	23	0	35	18	79	7%
3	729	0	16	16	0	118	13	151	21%
4	983	0	18	13	0	26	18	57	6%

MPC-85 – Evaporator 4

Effect - Pass	OHTC $W\ m^{-2}K^{-1}$	Term 1	2	3	4	5	6	Sum Terms	Uncertainty ± %
1-1	1976	0	74	26	0	171	36	271	14%
1-2	1900	0	55	33	0	136	29	224	12%
2-1	1469	0	48	8	0	161	27	216	15%
2-2	1451	0	50	10	0	152	26	213	15%
2-3	715	0	23	11	0	71	12	105	15%
2-4	5	0	0	16	0	-10	-2	7	121%
2-5	-229	0	-7	21	0	-39	-7	-25	11%
3	743	0	35	27	0	61	14	123	16%
4	1356	0	44	17	0	137	25	197	15%

Δ Wetting Rates

Skim Milk – Evaporator 1

Effect - Pass	Wetting Rate $kg\ m^{-1}s^{-1}$	Term 1	2	3	4	Sum Terms	Uncertainty ± %
1-1	0.133	0.0012	0.0014	0.0010	0.0024	0.006	5%
1-2	0.135	0.0012	0.0014	0.0009	0.0025	0.006	4%
2-1	0.149	0.0014	0.0015	0.0014	0.0027	0.007	5%
2-2	0.152	0.0014	0.0016	0.0011	0.0028	0.007	4%
2-3	0.135	0.0012	0.0014	0.0008	0.0025	0.006	4%
2-4	0.165	0.0015	0.0017	0.0009	0.0030	0.007	4%
2-5	0.202	0.0018	0.0021	0.0010	0.0037	0.009	4%
3	0.243	0.0022	0.0025	0.0011	0.0044	0.010	4%
4	0.185	0.0017	0.0019	0.0007	0.0034	0.008	4%

Skim Milk – Evaporator 4

Effect - Pass	Wetting Rate $kg\ m^{-1}s^{-1}$	Term 1	2	3	4	Sum Terms	Uncertainty ± %
1-1	0.134	0.0003	0.0013	0.0010	0.0025	0.005	4%
1-2	0.132	0.0003	0.0013	0.0008	0.0024	0.005	4%
2-1	0.150	0.0003	0.0015	0.0014	0.0027	0.006	4%
2-2	0.162	0.0003	0.0016	0.0012	0.0030	0.006	4%
2-3	0.144	0.0003	0.0014	0.0009	0.0026	0.005	4%
2-4	0.177	0.0004	0.0017	0.0009	0.0032	0.006	4%
2-5	0.213	0.0004	0.0021	0.0010	0.0039	0.007	4%
3	0.258	0.0005	0.0025	0.0012	0.0047	0.009	3%
4	0.198	0.0004	0.0019	0.0008	0.0036	0.007	3%

Whole Milk – Evaporator 1

Effect - Pass	Wetting Rate kg $m^{-1}s^{-1}$	Term 1	Term 2	Term 3	Term 4	Sum Terms	Uncertainty ± %
1-1	0.095	0.0008	0.0007	0.0006	0.0017	0.004	4%
1-2	0.101	0.0008	0.0007	0.0005	0.0019	0.004	4%
2-1	0.117	0.0010	0.0009	0.0009	0.0021	0.005	4%
2-2	0.130	0.0011	0.0010	0.0008	0.0024	0.005	4%
2-3	0.121	0.0010	0.0009	0.0007	0.0022	0.005	4%
2-4	0.156	0.0013	0.0011	0.0008	0.0028	0.006	4%
2-5	0.189	0.0016	0.0014	0.0009	0.0035	0.007	4%
3	0.227	0.0019	0.0017	0.0010	0.0041	0.009	4%
4	0.173	0.0014	0.0013	0.0007	0.0032	0.007	4%

Whole Milk – Evaporator 4

Effect - Pass	Wetting Rate kg $m^{-1}s^{-1}$	Term 1	Term 2	Term 3	Term 4	Sum Terms	Uncertainty ± %
1-1	0.095	0.0001	0.0007	0.0006	0.0017	0.003	3%
1-2	0.101	0.0001	0.0008	0.0005	0.0019	0.003	3%
2-1	0.118	0.0001	0.0009	0.0010	0.0022	0.004	4%
2-2	0.131	0.0001	0.0010	0.0009	0.0024	0.004	3%
2-3	0.120	0.0001	0.0009	0.0007	0.0022	0.004	3%
2-4	0.151	0.0002	0.0012	0.0008	0.0028	0.005	3%
2-5	0.184	0.0002	0.0014	0.0009	0.0034	0.006	3%
3	0.226	0.0002	0.0017	0.0010	0.0041	0.007	3%
4	0.175	0.0002	0.0013	0.0007	0.0032	0.005	3%

MPC-85 – Evaporator 4

Effect - Pass	Wetting Rate kg $m^{-1}s^{-1}$	Term 1	Term 2	Term 3	Term 4	Sum Terms	Uncertainty ± %
1-1	0.084	0.0002	0.0009	0.0007	0.0015	0.003	4%
1-2	0.085	0.0002	0.0009	0.0006	0.0015	0.003	4%
2-1	0.102	0.0002	0.0011	0.0012	0.0019	0.004	4%
2-2	0.116	0.0003	0.0013	0.0011	0.0021	0.005	4%
2-3	0.115	0.0003	0.0013	0.0010	0.0021	0.005	4%
2-4	0.162	0.0004	0.0018	0.0015	0.0030	0.007	4%
2-5	0.217	0.0005	0.0024	0.0020	0.0040	0.009	4%
3	0.272	0.0006	0.0030	0.0024	0.0050	0.011	4%
4	0.215	0.0005	0.0024	0.0017	0.0039	0.009	4%

A-10. Visual Basic code

Visual Basic Code was written by Ken Morison for the physical properties of water, milks, and water vapour. The programs are detailed below. The code appears in the following pages.

Program	Comments
WaterSatPressure	Antoine equation estimate
WaterSatPressure	NBS/NRC Steam Tables 1984
WaterSatTemperature	Inverse Antoine equation estimate
WaterVapDensity	From NBS/NRC Steam Tables 1984
WaterVapViscosity	From NBS/NRC Steam Tables 1984
WaterDensity	From NBS/NRC Steam Tables 1984
WaterViscosity	Equation suggested by R Gilmont CEP Oct 2002 p36
WaterThermalConductivity	From NBS/NRC Steam Tables 1984
WaterCp	Based on standard data, e.g. A J Chapman
WaterEnthalpy	Good 20-100 °C
WaterSatVapourEnthalpy	Good 20-100 °C
WaterVapourEnthalpy	Morison fit from data of Schmidt and NBS/NRC Steam tables. Some discrepancy between sources.
WaterLatentHeat	NBS/NRC Steam tables
WaterBPE	Berry *et al.* (1980), Physical Chemistry
WaterDensity	Good 5-100 °C.
MilkDensity	Jan Pisecky, Handbook of Milk Powder Manufacture, 1997
MilkDensityChoi	Based on Choi and Okos
MilkThermalConductivity	Based on Choi and Okos
WaterDensityChoi	For use with MilkDensityChoi
ProteinDensity	For use with MilkDensityChoi
FatDensity	For use with MilkDensityChoi
LactoseSolidDensity	For use with MilkDensityChoi
AshDensity	For use with MilkDensityChoi
MilkCp	Based on Choi and Okos
MilkViscosityFernadez	Fernadez-Martin J Dairy Res 39, 75 1972
MilkWholeViscTorsell	Milk Visc from Torsell for 3% fat
MilkSkimViscTorsell	From Torsell for 3% fat
MilkSkimViscSnoeren	From Snoeren *et al.* with help from Pisecky
MilkSkimPhiSnoeren	Snoeren *et al.* l with help from Pisecky
MilkViscJebson	JebsonJ Dairy Res, 1997, 64, 57-67
MilkViscBloore	Jebson J Dairy Res, 1997, 64, 57-67, based on Bloore
MilkViscosityEinstein	–
MilkViscosityExponential	–

Visual Basic Code in Excel
Written by Ken Morison

```
Option Explicit

'Function WaterSatPressure(Temp As Double) As Double
' Antoine type relation fitted by KRM.  Good 10-100°C
'Dim sExp As Double
'sExp = (23.423 - 3955.6 / (Temp + 232.5))
'WaterSatPressure = Exp(sExp)
'End Function
```

```
Function WaterSatPressure(Temp As Double) As Double
' From NBS/NRC fortran
' Temp in deg C, Pressure in Pa

Dim dA(8) As Double
Dim dTempK As Double
Dim dB As Double, DV As Double, dW As Double, DQ As Double
Dim i As Integer
dA(1) = -7.8889166: dA(2) = 2.5514255: dA(3) = -6.716169: dA(4) = 33.239495
dA(5) = -105.38479: dA(6) = 174.35319: dA(7) = -148.39348: dA(8) = 48.631602
dTempK = Temp + 273.15
If dTempK > 314 Then
   DV = dTempK / 647.25
   dW = Abs(1 - DV)
   dB = 0
   For i = 1 To 8
      dB = dB + dA(i) * dW ^ ((i + 1) / 2)
   Next i
   DQ = dB / DV
   WaterSatPressure = 22.093 * Exp(DQ) * 1000000
Else
   DQ = 6.3573118 - 8858.843 / dTempK + 607.5633 * dTempK ^ (-0.6)
   WaterSatPressure = Exp(DQ) * 100000
End If

End Function
```

```
Function WaterSatTemperature(Pressure As Double) As Double
' Inverse Antoine for first estimate
Dim sTemp As Double, sDiff As Double
Dim dPress As Double, dDPDT As Double
Dim icount As Integer

If Pressure > 0 Then
   sTemp = 3955.6 / (23.423 - WorksheetFunction.Ln(Pressure)) - 232.5
Else
   sTemp = 0
End If

icount = 0
Do
 icount = icount + 1
 dPress = WaterSatPressure(sTemp)
 sDiff = dPress - Pressure
 dDPDT = (WaterSatPressure(sTemp + 0.01) - dPress) / 0.01
 sTemp = sTemp - sDiff / dDPDT

Loop Until Abs(sDiff) < 0.00001 * Pressure Or icount > 10

WaterSatTemperature = sTemp

End Function
```

```
Function WaterVapDensity(Temp As Double, Optional Pressure As Variant) As Double
' from table data by KRM
' Best at saturation
If IsMissing(Pressure) Then
   Pressure = WaterSatPressure(Temp)
End If
WaterVapDensity = (Pressure * 0.01802 / 8.314 / (Temp + 273.15)) * (1.0002858 + 0.00002775 * Temp + 0.000000186 * Temp ^ 2 + 0.0000000103 * Temp ^ 3)

' WaterVapDensity = 0.002133 * WaterSatPressure(Temp) / (Temp + 273.15) + 0.00000000000431 * WaterSatPressure(Temp) ^ 2
End Function
```

```
Function WaterVapViscosity(Temp As Double) As Double
' from data from NBS/NRC Steam Tables 1984 correlation by KRM
' Good 10 to 140 °C, max error 0.2%
WaterVapViscosity = (0.000032234 * (Temp + 273.15) ^ 2 + 0.010207 * (Temp + 273.15) + 3.9661) / 1000000
End Function
```

Function WaterDensity(Temp As Double) As Double
' Water density good 5-100 °C
' curve fit by KRM

'1.50673E-05x3 - 5.75036E-03x2 + 4.08490E-03x + 1.00035E+03
WaterDensity = 1000.35 + 0.004085 * Temp - 0.0057504 * Temp ^ 2 + 0.0000150673 * Temp ^ 3
End Function

Function WaterViscosity(Temp As Double) As Double
' Water viscosity in Pa.s, optimized for the range 0 to 100 °C
' uses equation suggested by R Gilmont CEP Oct 2002 p36
' based on viscosity at 20 °C with two constants
WaterViscosity = 0.001002 * Exp(574.81 * (1 / (Temp + 133.732) - 1 / (20 + 133.732)))

End Function

Function WaterThermalConductivity(Temp As Double) As Double
' Thermal conductivity from data in A J Chapman curve by KRM
' WaterThermalConductivity = 0.56561 + 0.0018379*Temp-0.000007109*Temp ^ 2
' From NBS/NRC Steam tables
WaterThermalConductivity = 0.5603 + 0.002124 * Temp - 0.000009374 * Temp ^ 2

End Function

Function WaterCp(Temp As Double) As Double
' Water specific heat J/kg K based on standard data, e.g. A J Chapman
WaterCp = 4198 - 0.86593 * Temp + 0.010475 * Temp ^ 2
End Function

Function WaterEnthalpy(Temp As Double) As Double
' in J/kg. Good 20-100 °C
WaterEnthalpy = 88.22 + 4186.7 * Temp
End Function

Function WaterSatVapourEnthalpy(Temp As Double) As Double
' Saturated Vapour Enthalpy in J/kg. Good 20-100 °C
WaterSatVapourEnthalpy = -1.568182 * Temp ^ 2 + 1916.348 * Temp + 2500277#
End Function

Function WaterSatVapourEntropy(Temp As Double) As Double
' Saturated Vapour Entropy in J/kgK
' Max error 0.13% in range 0 to 100 °C
' Morison fit from data of Schmidt
WaterSatVapourEntropy=(0.000071818*Temp^2-0.025016*Temp+9.1482)*1000
End Function

Function WaterVapourEnthalpy(Temp As Double, Pressure As Double) As Double
' Vapour Enthalpy in J/kg
' Max error in range 0 to 100 °C less than 0.04%
' Morison fit from data of Schmidt and NBS/NRC Steam tables
' Some discrepancy between the two sources.
Dim sSatTemp As Double
sSatTemp = WaterSatTemperature(Pressure)
WaterVapourEnthalpy = WaterSatVapourEnthalpy(sSatTemp) + 1904 * (Temp - sSatTemp)
End Function

Function WaterVapourEntropy(Temp As Double, Pressure As Double) As Double
' Vapour Entropy in J/kgK
' Max error in range 0 to 100 °C
' Uses s2-s1 = Cp ln(T2/T1) at constant P
Dim sSatTemp As Double
sSatTemp = WaterSatTemperature(Pressure)
WaterVapourEntropy = WaterSatVapourEntropy(sSatTemp) + 1904 * Log((Temp + 273.15) / (sSatTemp + 273.15))
End Function

Function WaterLatentHeat(Temp As Double) As Double
WaterLatentHeat = WaterSatVapourEnthalpy(Temp) - WaterEnthalpy(Temp)
End Function

Function WaterDensity(Temp As Double) As Double
' Water density good 5-100 °C
' curve fit by KRM

'1.50673E-05x3 - 5.75036E-03x2 + 4.08490E-03x + 1.00035E+03
WaterDensity = 1000.35 + 0.004085 * Temp - 0.0057504 * Temp ^ 2 + 0.0000150673 * Temp ^ 3
End Function

```
Function WaterBPE(Temp_C As Double, WaterActivity As Double) As Double
' Calc BPE with second order terms also
' based on Berry et al. (1980), Physical Chemistry
' Temp is pure water BP in deg C

Dim dA As Double, dB As Double, dC As Double  ' quadratic terms
Dim dR As Double, dHv As Double, dT_K As Double

dR = 8.314
dHv = 0.01805 * WaterLatentHeat(Temp_C)
dT_K = Temp_C + 273.15
dC = -Log(WaterActivity)
dB = -dHv / dR / dT_K ^ 2
dA = (0.01805 * (WaterCp(Temp_C) - 1904) / 2 / dR + dHv / dR / dT_K) / dT_K ^ 2

WaterBPE = (-dB - Sqr(dB ^ 2 - 4 * dA * dC)) / 2 / dA

End Function
```

```
Function MilkDensity(Temp As Double, NFS As Double, Fat As Double)
' Density of milk based on Jan Pisecky, Handbook of Milk Powder Manufacture, 1997
' Temp is temperature in deg C, NFS is mass fraction on non-fat solids
' Fat is mass fraction of fat
Dim dRhoFat As Double, dRhoNFS As Double, dRhoWater As Double

dRhoFat = 966.665 - 1.334 * Temp
dRhoNFS = 1635 - 2.6 * Temp + 0.02 * Temp ^ 2
dRhoWater = WaterDensity(Temp)

MilkDensity = 1 / (Fat / dRhoFat + NFS / dRhoNFS + (1 - Fat - NFS) / dRhoWater)
End Function
```

```
Function MilkDensityChoi(Temp As Double, Protein As Double, Lactose As Double, Fat As Double, Ash As Double) As Double
' Density based on Choi and Okos
' Temp is temperature in deg C, Protein, Lactose, Fat and Ash (minerals) are mass fractions

 MilkDensityChoi = 1 / Fat / FatDensity(Temp) + Protein / ProteinDensity(Temp) + Lactose / LactoseSolidDensity(Temp) + Ash / AshDensity(Temp) + (1 - Fat - Protein - Lactose - Ash) / WaterDensityChoi(Temp))

 End Function
```

```
Function MilkThermalConductivity(Temp As Double, Protein As Double, Lactose As Double, Fat As Double, Ash As Double) As Double
' Thermal conductivity of milk based foods
' Based on Choi and Okos
Dim sVolWater As Double, sVolProtein As Double, sVolLactose As Double
Dim sVolAsh As Double, sVolFat As Double

sVolProtein = Protein / ProteinDensity(Temp)
sVolLactose = Lactose / LactoseSolidDensity(Temp)
sVolFat = Fat / FatDensity(Temp)
sVolAsh = Ash / AshDensity(Temp)
' Assume all the remainder is water
sVolWater = (1 - Protein - Lactose - Fat - Ash) / WaterDensityChoi(Temp)

MilkThermalConductivity = (sVolWater * WaterThermalConductivity(Temp) + sVolProtein * ProteinThermalConductivity(Temp) + sVolLactose * LactoseThermalConductivity(Temp) + sVolFat * FatThermalConductivity(Temp) + sVolAsh * AshThermalConductivity(Temp)) / (sVolWater + sVolProtein + sVolLactose + sVolFat + sVolAsh)

End Function
```

```
Function WaterDensityChoi(Temp As Double) As Double
' for use with MilkDensityChoi
WaterDensityChoi = 997.2 - 0.00314 * Temp - 0.00376 * Temp ^ 2
End Function
```

```
Function ProteinDensity(Temp As Double) As Double
' for use with MilkDensityChoi
ProteinDensity = 1329.9 - 0.5184 * Temp
End Function
```

```
Function FatDensity(Temp As Double) As Double
' for use with MilkDensityChoi
FatDensity = 925.59 - 0.41757 * Temp
End Function
```

```
Function LactoseSolidDensity(Temp As Double) As Double
' for use with MilkDensityChoi
LactoseSolidDensity = 1599.1 - 0.31046 * Temp
End Function
```

```
Function AshDensity(Temp As Double) As Double
' for use with MilkDensityChoi
AshDensity = 2423.8 - 0.28063 * Temp
End Function
```

```
Private Function ProteinThermalConductivity(Temp As Double) As Double
ProteinThermalConductivity = 0.17881 + 0.0011958*Temp-0.0000027178*Temp ^ 2
End Function

Private Function LactoseThermalConductivity(Temp As Double) As Double
LactoseThermalConductivity = 0.20141+0.0013874*Temp-0.0000043312 * Temp ^ 2
End Function

Private Function FatThermalConductivity(Temp As Double) As Double
FatThermalConductivity = 0.18071-0.0027604*Temp-0.00000017749 * Temp ^ 2
End Function

Private Function AshThermalConductivity(Temp As Double) As Double
AshThermalConductivity = 0.32962 + 0.0014011*Temp - 0.0000029069*Temp ^ 2
End Function
```

```
Function MilkCp(Temp As Double, Protein As Double, _
  Lactose As Double, Fat As Double, Ash As Double) As Double
' Specific heat capacity based on Choi and Okos
Dim sProteinCp As Double
Dim sLactoseCp As Double
Dim sFatCp As Double
Dim sAshCp As Double

sProteinCp = 2008.2 + 1.2089 * Temp - 0.0013129 * Temp ^ 2
sLactoseCp = 1548.8 + 1.9625 * Temp - 0.0059399 * Temp ^ 2
sFatCp = 1984.2 + 1.4733 * Temp - 0.0048008 * Temp ^ 2
sAshCp = 1092.6 + 1.8896 * Temp - 0.0036817 * Temp ^ 2

MilkCp = Protein * sProteinCp + Lactose * sLactoseCp + Fat * sFatCp + Ash * sAshCp + (1 - Protein - Lactose - Fat - Ash) * WaterCp(Temp)

End Function
```

```
Function MilkViscosityFernadez(Temp As Double, TS As Double) As Double
' from Fernadez-Martin J Dairy Res 39, 75 1972
' For 0 to 30% TS, 0-80°C
'not used (Steve)

Dim sLnVisc
sLnVisc = 0.249 - 0.013 * Temp + 0.000052 * Temp ^ 2 + (0.02549 - 0.000098 * Temp + 0.0000004 * Temp ^ 2) * TS * 100 _
   + (0.000543 - 0.0000139 * Temp + 0.000000117 * Temp ^ 2) * TS ^ 2 * 10000

MilkViscosityFernadez = 10 ^ (sLnVisc) / 1000

End Function
```

```
Function MilkWholeViscTorsell(Temp As Double, TS As Double) As Double
' Milk Visc from Torsell for 3% fat
'use for whole milk

Dim sLogT As Double
Dim sDensity As Double
sDensity = MilkDensity(Temp, 0.75 * TS, 0.25 * TS) ' kg/m3

sLogT = WorksheetFunction.Log10((Temp + 273.15) / 313)  ' natural log assumed

MilkWholeViscTorsell = 10 ^ (10 ^ (-(TS * 100 * (-0.0708 * sLogT - 0.0199) + 7.011 * sLogT + 0.8055))) - 0.8
MilkWholeViscTorsell = MilkWholeViscTorsell / 1000000# * sDensity
End Function
```

```
Function MilkSkimViscTorsell(Temp As Double, TS As Double) As Double
' Milk Visc from Torsell
'use for skim milk

Dim sLogT As Double
Dim sDensity As Double
sDensity = MilkDensity(Temp, TS, 0) ' kg/m3
sLogT = WorksheetFunction.Log10((Temp + 273.15) / 313)  ' natural log assumed

MilkSkimViscTorsell = 10 ^ (10 ^ (-(TS * 100 * (-0.0876 * sLogT - 0.02243) + 7.806 * sLogT + 0.844))) - 0.8
MilkSkimViscTorsell = MilkSkimViscTorsell / 1000000# * sDensity

End Function
```

```
Function MilkViscosityExponential(Temp As Double, Casein As Double, Whey As Double, Lactose As Double, Fat As Double, TS As Double) As Double

Dim dEA As Double, dRelVisc As Double
Dim sAWhey As Single, sACasein As Single, sAFat As Single
Dim sALactose As Single, sBCasein As Single, sBFat As Single
Dim dWater As Double

dWater = 1 - TS

sAWhey = 11.27
sACasein = 9.9  ' Casein values based on Eilers
sBCasein = 3.4

sALactose = 2.85
sAFat = 3# ' (good for Phipps cream data)
sBFat = -0.66
   dRelVisc = Exp(sAWhey * Whey / dWater + sACasein * Casein / dWater + _
      sBCasein * (Casein / dWater) ^ 2 + sALactose * Lactose / dWater + _
      sAFat * Fat / dWater + sBFat * (Fat / dWater) ^ 2)

   MilkViscosityExponential = dRelVisc * WaterViscosity(Temp)
End Function
```

```
Function MilkSkimViscSnoeren(Temp As Double, TS As Double, Casein As Double, Fat As Double, WheyNative As Double, WheyDenatured As Double) As Double
'  From Snoeren et al with help from Pisecky
' All components are mass fraction, Temp in deg C
'don't use (Steve)

Dim sDensity As Double, sPhiMilk As Double, sViscRef As Double
Dim sViscWater As Double, sViscLactose As Double

sDensity = MilkDensity(Temp, TS - Fat, Fat)
sViscWater = 1.66 - 0.036244*Temp+0.00033276*Temp^2-0.0000010631*Temp ^ 3
sViscLactose = 0.102977 - 0.000603 * Temp
sPhiMilk = (Casein * 3.57 + WheyDenatured * 3.09 + WheyNative * 1.07 + Fat * 1.075) * sDensity / 1000

sViscRef = (sViscWater + (0.02 * sViscWater + sViscLactose) * TS / 0.1) / 1000
MilkSkimViscSnoeren = sViscRef * (1 + (1.25 * sPhiMilk) / (1 - sPhiMilk / 0.79))^ 2
End Function
```

```
Function MilkSkimPhiSnoeren(Temp As Double, TS As Double, Casein As Double, Fat As Double, WheyNative As Double, WheyDenatured As Double) As Double
'  From Snoeren et al with help from Pisecky
' All components are mass fraction, Temp in deg C

Dim sDensity As Double, sPhiMilk As Double, sViscRef As Double
Dim sViscWater As Double, sViscLactose As Double

sDensity = MilkDensity(Temp, TS - Fat, Fat)
sViscWater = 1.66-0.036244*Temp+0.00033276*Temp^2-0.0000010631*Temp^3
sViscLactose = 0.102977 - 0.000603 * Temp
MilkSkimPhiSnoeren = (Casein * 3.57 + WheyDenatured * 3.09 + WheyNative * 1.07 + Fat * 1.075) * sDensity / 1000

End Function
```

```
Function MilkViscJebson(Temp As Double, TS As Double, Fat As Double) As Double
' From JebsonJ Dairy Res, 1997, 64, 57-67
' Temp in deg C, TS, Fat in mass fraction

Dim sDensity As Double, sVisc As Double
sDensity = MilkDensity(Temp, TS - Fat, Fat)

sVisc = 10 ^ (10 ^ (-0.229 - 0.18 * WorksheetFunction.Log10(Temp + 273.15) + 0.042 * TS / 1000 + 0.00034 * (TS / 1000) ^ 2)) - 0.8
MilkViscJebson = sVisc * sDensity
End Function
```

```
Function MilkViscBloore(Temp As Double, TS As Double) As Double
' From Jebson J Dairy Res, 1997, 64, 57-67, based on Bloore
' Temp in deg C, TS, Fat in mass fraction
' for TS > 0.45, originally for skim but used for wholemilk by Jebson

MilkViscBloore = Exp(3.911 + 0.0202 * (TS * 1000 - 482.5) / 0.85 - 0.1291 * (Temp - 52.5) / 7.5) / 1000

End Function
```

```
Function MilkViscosityEinstein(Temp As Double, Casein As Double, Whey As Double, Lactose As Double, Fat As Double) As Double

Dim dEA As Double, dRelVisc As Double
Dim dTS As Double, sPhi As Single
Dim sVolWhey As Single, sVolCasein As Single, sVolFat As Single
Dim sVolLactose As Single

sVolWhey = 0.00375
sVolCasein = 0.0022
sVolLactose = 0.0012
sVolFat = 0.00173
sVolFat = 0.0014

'  needs changing for casein in high concentrations

If Casein + Whey > 0.15 Then
   MilkViscosityEinstein = 0.00069 * Exp(16 * (1 + 3 * Lactose) * (Casein + Whey))
   ' Temperature correction
   dTS = Casein + Whey + Fat + Lactose
   dEA = 16500 - 3440 * dTS + 116000 * dTS ^ 2 ' J/mol
   MilkViscosityEinstein = MilkViscosityEinstein * _
      Exp(dEA / 8.314 * (1 / (273.15 + Temp) - 1 / 297.15))
Else
   sPhi = MilkDensity(Temp, Casein + Whey + Lactose, Fat) * _
      (Lactose * sVolLactose + Whey * sVolWhey + Fat * sVolFat + Casein * sVolCasein)
   dRelVisc = EinsteinRelVisc(sPhi)
   MilkViscosityEinstein = dRelVisc * WaterViscosity(Temp)
End If

End Function
```

A-11. Total solids results for skim milk on 14 September 2004

These total solids samples were taken when there were rapid increases in the MVR fan speeds in Evaporator 1. The measurements were taken 3 and 8 hours after start-up. A preheater swap occurred at 6 hours.

Effect – Pass Outlet	Total Solids out of Pass [%] Hour 3	Hour 8
Feed	9.4	9.4
1-1	12.4	12.4
1-2	15.4	15.5
2-1	22.7	26.3
2-2	28.1	33.5
2-3	33.9	40.7
2-4	38.9	44.0
2-5	41.4	40.2
4-1	51.1	50.6

There was an uncertainty of ± 0.001 TS for milks with concentrations below 20% TS (0.20 mass fraction). The uncertainty for milk concentrates at or above 20% TS was ± 0.3% TS.

A-12. Pressure drop calculations

A-12.1 Pressure drop equation

The equation below is found from fluid mechanics notes by Morison (2002). This is for a heated vertical pipe under evaporation.

$$-\frac{dP}{dx} = \left(\frac{2\,fG^2 v_v}{D} + 2v_v G\left(\frac{4U\Delta T}{D\Delta h_v} \right) + \frac{g}{v_v} \right) \Big/ \left(1 + G^2 \frac{dv_G}{dP} \right)$$

This was separated into four terms and calculated for 1 m lengths of the pipe, and integrated to give an overall pressure drop. These are shown below.

Term	Equation
1	$\frac{2\,fG^2 v_v}{d_i}$
2	$2v_v G\left(\frac{4U\Delta T}{d_i \Delta h_v} \right)$
3	$\frac{g}{v_v}$
4	$1 + G^2 \frac{dv_G}{dP}$
$-\frac{dP}{dx}$	$-\frac{dP}{dx} = \frac{\text{Term}\,1 + \text{Term}\,2 + \text{Term}\,3}{\text{Term}\,4}$

The other equations required are shown below.

- $\mathrm{G} = \frac{4\mathrm{U}\Delta\mathrm{T}}{\mathrm{d_i}\ \Delta\mathrm{H_v}} + \mathrm{G_{in}}$
- $\mathrm{Re} = \frac{\mathrm{G\ d_i}}{\mu}$
- $\mathrm{f} = \frac{16}{\mathrm{Re}}$ if $\mathrm{Re} < 2000$
- $\mathrm{f} = \frac{0.076}{\mathrm{Re}^{0.25}}$ if $\mathrm{Re} \geq 2000$

A-12.2 Calculation method

The tube was divided into 14 segments which were each 1 m long. The pressure at the bottom was known, but not at the top. A pressure was guessed at the top, and calculations were made for the inlet and outlet pressures, temperatures and mass fluxes in each segment, beginning at the top. Microsoft Excel Solver was used to iteratively change the guessed pressure at the top so that the calculated and measured pressures at the bottom were equal. This is shown below in Figure A-12.

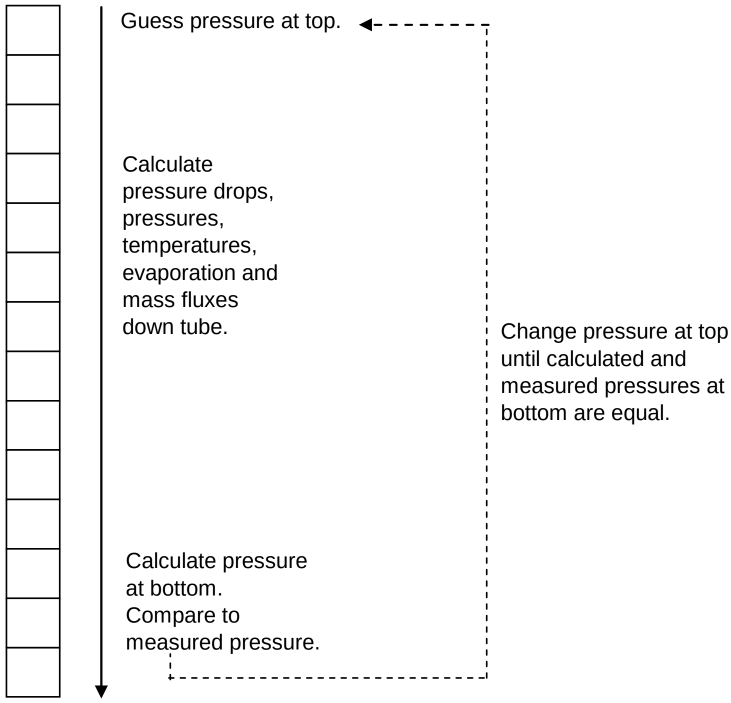


Figure A-12: Method of calculating the pressure drops down the tubes in each pass using Microsoft Excel and Solver.

The tube had dimensions of diameter (d_i). Gravity was important because the tubes were vertical. The effect had a shell-to-effect temperature difference which was assumed constant over the 1 m segment.

The liquid entering had an overall heat transfer coefficient (U) and enthalpy of vaporisation (Δh_v). There was an input mass flux (G) to the segment. This had a vapour volume (v_v) and a constant dv_G/dP of approximately -0.004, which was found from steam tables.

The Reynolds number was calculated for the water vapour. This was used to find the friction factor for the water vapour. The evaporation rate in the segment was calculated. The sum of the inlet mass flux and evaporation of water gave the outlet mass flux.

A-12.3 Calculations

The pressure drop due to evaporation was calculated. This gave the pressure at the bottom of each segment. The outlet pressure and temperature were calculated.

An example of the calculations are shown below. These are for skim milk in Evaporator 4 on 27 Feb 2004. They are divided into the input data, the resultant pressures calculated down the tube and the pressure drop calculations for each pass.

Input Data

Effect – Pass	Shell Temperature ºC	Effect Temperature ºC	U W/m2.K	d_i m	ΔT ºC	Inlet flow kg/hr	Total Solids Outlet %
Feed		86.0			16.8		10
1-1	72.3	69.2	2123	0.0486	3.1	62936	13
1-2	72.3	69.2	2195	0.0486	3.1	48075	17
2-1	68.6	65.0	2116	0.0487	3.6	37460	22
2-2	68.6	65.0	2021	0.0488	3.6	29324	27
2-3	68.6	65.0	1609	0.0488	3.6	23630	33
2-4	68.6	65.0	1400	0.0489	3.6	19529	38
2-5	68.6	65.0	1186	0.0489	3.6	17084	41
3-1	60.3	56.7	1067	0.0489	3.6	15510	45
4-1 96 tubes	55.7	50.0	680	0.0489	5.7	14347	49
To drier						13031	

Iteration

Used Solver to change P top so that P sensor bottom = P bottom calc

Effect – Pass	P top Pa	P sensor bottom (a) Pa	P bottom calc (b) Pa	|a - b| Pa	ΔP Pa	T top ºC	ΔT length ºC
Feed							
1-1	30347	30146	30146	0	201	69.4	0.15
1-2	30356	30146	30146	0	211	69.4	0.16
2-1	25294	25041	25041	0	253	65.2	0.23
2-2	25275	25041	25041	0	234	65.2	0.21
2-3	25203	25041	25041	0	162	65.2	0.14
2-4	25172	25041	25041	0	131	65.1	0.12
2-5	25144	25041	25041	0	103	65.1	0.09
3	17252	17094	17094	0	157	56.9	0.19
4, 96 tubes	12530	12356	12356	0	174	50.3	0.28
4, 80 tubes	12593	12356	12356	0	238	50.4	0.38

Effect 1-1

L	P	T	V-v	G	Re	f	Terms				ΔP
	Pa	°C	$m^3 kg^{-1}$	[-]	[-]	[-]	1	2	3	4	Pa
0	30347	69.4	5.17	0.25	1084	0.0148	0.20	0.60	1.896	-2.5E-05	2.7
1	30344	69.4	5.17	0.48	2077	0.0077	0.38	1.14	1.896	-9.2E-05	3.4
2	30341	69.4	5.17	0.71	3070	0.0102	1.10	1.69	1.896	-2.0E-04	4.7
3	30336	69.4	5.18	0.94	4063	0.0095	1.79	2.23	1.895	-3.5E-04	5.9
4	30330	69.4	5.18	1.17	5056	0.0090	2.62	2.78	1.895	-5.5E-04	7.3
5	30323	69.4	5.18	1.40	6049	0.0086	3.59	3.33	1.895	-7.8E-04	8.8
6	30314	69.4	5.18	1.63	7042	0.0083	4.69	3.87	1.894	-1.1E-03	10.5
7	30303	69.3	5.18	1.86	8035	0.0080	5.91	4.42	1.894	-1.4E-03	12.2
8	30291	69.3	5.18	2.09	9028	0.0078	7.25	4.97	1.893	-1.7E-03	14.1
9	30277	69.3	5.18	2.32	10021	0.0076	8.71	5.52	1.892	-2.1E-03	16.2
10	30261	69.3	5.19	2.55	11015	0.0074	10.28	6.07	1.891	-2.6E-03	18.3
11	30243	69.3	5.19	2.78	12008	0.0073	11.96	6.62	1.890	-3.1E-03	20.5
12	30222	69.3	5.19	3.01	13001	0.0071	13.75	7.17	1.889	-3.6E-03	22.9
13	30199	69.3	5.20	3.24	13994	0.0070	15.65	7.73	1.887	-4.2E-03	25.4
14	30174	69.2	5.20	3.47	14987	0.0069	17.66	8.28	1.886	-4.8E-03	28.0
	30146			3.70							
	ΔPtotal	201	Pa	m_{evap}	11124	$kg\ h^{-1}$					

Effect 1-2

L	P	T	V-v	G	Re	f	Terms				ΔP
	Pa	°C	$m^3 kg^{-1}$	[-]	[-]	[-]	1	2	3	4	Pa
0	30356	69.4	5.17	0.25	1083	0.0148	0.20	0.61	1.897	-2.5E-05	2.7
1	30354	69.4	5.17	0.49	2110	0.0076	0.38	1.20	1.897	-9.5E-05	3.5
2	30350	69.4	5.17	0.72	3136	0.0102	1.14	1.78	1.896	-2.1E-04	4.8
3	30345	69.4	5.17	0.96	4163	0.0095	1.86	2.36	1.896	-3.7E-04	6.1
4	30339	69.4	5.17	1.20	5190	0.0090	2.74	2.95	1.896	-5.8E-04	7.6
5	30332	69.4	5.18	1.44	6216	0.0086	3.76	3.53	1.895	-8.3E-04	9.2
6	30322	69.4	5.18	1.67	7243	0.0082	4.92	4.11	1.895	-1.1E-03	10.9
7	30312	69.4	5.18	1.91	8269	0.0080	6.20	4.70	1.894	-1.5E-03	12.8
8	30299	69.3	5.18	2.15	9296	0.0077	7.62	5.28	1.893	-1.8E-03	14.8
9	30284	69.3	5.18	2.39	10322	0.0075	9.15	5.87	1.892	-2.3E-03	17.0
10	30267	69.3	5.19	2.62	11349	0.0074	10.81	6.46	1.891	-2.8E-03	19.2
11	30248	69.3	5.19	2.86	12375	0.0072	12.58	7.04	1.890	-3.3E-03	21.6
12	30226	69.3	5.19	3.10	13402	0.0071	14.48	7.63	1.889	-3.8E-03	24.1
13	30202	69.3	5.20	3.34	14429	0.0069	16.49	8.22	1.888	-4.4E-03	26.7
14	30175	69.2	5.20	3.57	15455	0.0068	18.61	8.82	1.886	-5.1E-03	29.5
	30146			3.81							
	ΔPtotal	211	Pa	m_{evap}	13109	$kg\ h^{-1}$					

Effect 2-1

L	P	T	V-v	G	Re	f	Terms				ΔP
	Pa	°C	$m^3\ kg^{-1}$	[-]	[-]	[-]	1	2	3	4	Pa
0	25294	65.2	6.14	0.04	175	0.0916	0.04	0.13	1.598	-6.3E-07	1.8
1	25293	65.2	6.14	0.31	1339	0.0119	0.28	1.00	1.598	-3.7E-05	2.9
2	25290	65.2	6.14	0.57	2504	0.0064	0.52	1.86	1.598	-1.3E-04	4.0
3	25286	65.2	6.14	0.84	3668	0.0098	1.72	2.73	1.598	-2.8E-04	6.0
4	25280	65.2	6.14	1.10	4833	0.0091	2.79	3.59	1.598	-4.9E-04	8.0
5	25272	65.2	6.14	1.37	5997	0.0086	4.07	4.46	1.597	-7.5E-04	10.1
6	25261	65.2	6.14	1.63	7162	0.0083	5.56	5.33	1.597	-1.1E-03	12.5
7	25249	65.2	6.15	1.90	8326	0.0080	7.24	6.20	1.596	-1.4E-03	15.1
8	25234	65.2	6.15	2.16	9491	0.0077	9.11	7.07	1.595	-1.9E-03	17.8
9	25216	65.2	6.15	2.43	10655	0.0075	11.16	7.94	1.594	-2.4E-03	20.7
10	25195	65.2	6.16	2.69	11820	0.0073	13.39	8.82	1.593	-2.9E-03	23.9
11	25172	65.1	6.17	2.96	12984	0.0071	15.80	9.69	1.591	-3.5E-03	27.2
12	25144	65.1	6.17	3.23	14149	0.0070	18.38	10.57	1.590	-4.2E-03	30.7
13	25114	65.1	6.18	3.49	15313	0.0068	21.13	11.46	1.588	-4.9E-03	34.3
14	25079	65.0	6.19	3.76	16478	0.0067	24.06	12.34	1.586	-5.6E-03	38.2
	25041			4.02							
	ΔPtotal	253	Pa	m_{evap}	8438	$kg\ h^{-1}$					

Effect 2-2

L	P	T	V-v	G	Re	f	Terms				ΔP
	Pa	°C	$m^3\ kg^{-1}$	[-]	[-]	[-]	1	2	3	4	Pa
0	25275	65.2	6.14	0.04	174	0.0917	0.04	0.12	1.597	-6.3E-07	1.8
1	25273	65.2	6.14	0.29	1287	0.0124	0.27	0.91	1.597	-3.4E-05	2.8
2	25271	65.2	6.14	0.55	2399	0.0067	0.50	1.70	1.597	-1.2E-04	3.8
3	25267	65.2	6.14	0.80	3512	0.0099	1.59	2.49	1.597	-2.6E-04	5.7
4	25261	65.2	6.14	1.05	4624	0.0092	2.57	3.28	1.597	-4.4E-04	7.5
5	25254	65.2	6.15	1.31	5737	0.0087	3.75	4.07	1.596	-6.8E-04	9.4
6	25244	65.2	6.15	1.56	6849	0.0084	5.12	4.86	1.596	-9.7E-04	11.6
7	25233	65.2	6.15	1.81	7962	0.0080	6.67	5.65	1.595	-1.3E-03	13.9
8	25219	65.2	6.15	2.07	9074	0.0078	8.39	6.44	1.594	-1.7E-03	16.4
9	25202	65.2	6.16	2.32	10187	0.0076	10.27	7.23	1.593	-2.2E-03	19.1
10	25183	65.1	6.16	2.57	11299	0.0074	12.33	8.03	1.592	-2.6E-03	22.0
11	25161	65.1	6.17	2.83	12412	0.0072	14.54	8.83	1.591	-3.2E-03	25.0
12	25136	65.1	6.17	3.08	13524	0.0070	16.91	9.63	1.589	-3.8E-03	28.2
13	25108	65.1	6.18	3.33	14637	0.0069	19.44	10.43	1.587	-4.4E-03	31.6
14	25076	65.0	6.19	3.59	15749	0.0068	22.13	11.24	1.586	-5.1E-03	35.1
	25041			3.84							
	ΔPtotal	234	Pa	m_{evap}	6313	$kg\ h^{-1}$					

Effect 2-3

L	P	T	V-v	G	Re	f	Terms				ΔP
	Pa	°C	$m^3\ kg^{-1}$	[-]	[-]	[-]	1	2	3	4	Pa
0	25203	65.2	6.16	0.04	174	0.0918	0.04	0.10	1.593	-6.3E-07	1.7
1	25201	65.2	6.16	0.24	1060	0.0151	0.22	0.60	1.593	-2.3E-05	2.4
2	25199	65.2	6.16	0.44	1945	0.0082	0.41	1.10	1.593	-7.8E-05	3.1
3	25196	65.2	6.16	0.64	2831	0.0057	0.59	1.60	1.593	-1.7E-04	3.8
4	25192	65.2	6.16	0.85	3716	0.0097	1.75	2.10	1.592	-2.9E-04	5.4
5	25186	65.1	6.16	1.05	4602	0.0092	2.55	2.60	1.592	-4.4E-04	6.7
6	25180	65.1	6.16	1.25	5487	0.0088	3.47	3.10	1.592	-6.2E-04	8.2
7	25172	65.1	6.17	1.45	6373	0.0085	4.51	3.60	1.591	-8.4E-04	9.7
8	25162	65.1	6.17	1.65	7258	0.0082	5.67	4.10	1.591	-1.1E-03	11.4
9	25150	65.1	6.17	1.85	8143	0.0080	6.94	4.60	1.590	-1.4E-03	13.1
10	25137	65.1	6.17	2.05	9029	0.0078	8.31	5.11	1.589	-1.7E-03	15.0
11	25122	65.1	6.18	2.25	9914	0.0076	9.80	5.61	1.588	-2.0E-03	17.0
12	25105	65.1	6.18	2.46	10800	0.0075	11.39	6.11	1.587	-2.4E-03	19.1
13	25086	65.1	6.18	2.66	11685	0.0073	13.08	6.62	1.586	-2.8E-03	21.3
14	25065	65.0	6.19	2.86	12571	0.0072	14.87	7.13	1.585	-3.3E-03	23.7
	25041			3.06							
	ΔPtotal	162	Pa	m_{evap}	4576	$kg\ h^{-1}$					

Effect 2-4

L	P	T	V-v	G	Re	f	Terms				ΔP
	Pa	°C	$m^3\ kg^{-1}$	[-]	[-]	[-]	1	2	3	4	Pa
0	25172	65.1	6.17	0.04	174	0.0919	0.04	0.09	1.591	-6.2E-07	1.7
1	25170	65.1	6.17	0.21	945	0.0169	0.20	0.46	1.591	-1.8E-05	2.3
2	25168	65.1	6.17	0.39	1715	0.0093	0.36	0.84	1.591	-6.1E-05	2.8
3	25165	65.1	6.17	0.56	2486	0.0064	0.52	1.22	1.591	-1.3E-04	3.3
4	25162	65.1	6.17	0.74	3257	0.0101	1.39	1.60	1.591	-2.2E-04	4.6
5	25157	65.1	6.17	0.91	4027	0.0095	2.01	1.97	1.590	-3.3E-04	5.6
6	25152	65.1	6.17	1.09	4798	0.0091	2.74	2.35	1.590	-4.7E-04	6.7
7	25145	65.1	6.17	1.26	5569	0.0088	3.55	2.73	1.590	-6.4E-04	7.9
8	25137	65.1	6.17	1.44	6339	0.0085	4.46	3.11	1.589	-8.3E-04	9.2
9	25128	65.1	6.18	1.61	7110	0.0083	5.45	3.49	1.589	-1.0E-03	10.5
10	25117	65.1	6.18	1.79	7881	0.0081	6.53	3.87	1.588	-1.3E-03	12.0
11	25105	65.1	6.18	1.96	8651	0.0079	7.69	4.25	1.587	-1.5E-03	13.5
12	25092	65.1	6.18	2.14	9422	0.0077	8.93	4.63	1.586	-1.8E-03	15.2
13	25077	65.0	6.19	2.31	10193	0.0076	10.25	5.01	1.586	-2.1E-03	16.9
14	25060	65.0	6.19	2.49	10963	0.0074	11.66	5.39	1.585	-2.5E-03	18.7
	25041			2.66							
	ΔPtotal	131	Pa	m_{evap}	2742	$kg\ h^{-1}$					

Effect 2-5

L	P	T	V-v	G	Re	f	Terms				ΔP
	Pa	°C	$m^3\ kg^{-1}$	[-]	[-]	[-]	1	2	3	4	Pa
0	25144	65.1	6.17	0.04	174	0.0919	0.04	0.07	1.590	-6.2E-07	1.7
1	25142	65.1	6.17	0.19	827	0.0194	0.17	0.34	1.589	-1.4E-05	2.1
2	25140	65.1	6.17	0.34	1480	0.0108	0.31	0.61	1.589	-4.5E-05	2.5
3	25138	65.1	6.17	0.48	2133	0.0075	0.44	0.89	1.589	-9.4E-05	2.9
4	25135	65.1	6.17	0.63	2785	0.0057	0.58	1.16	1.589	-1.6E-04	3.3
5	25131	65.1	6.17	0.78	3438	0.0099	1.53	1.43	1.589	-2.4E-04	4.5
6	25127	65.1	6.18	0.93	4091	0.0095	2.07	1.70	1.589	-3.5E-04	5.4
7	25121	65.1	6.18	1.08	4744	0.0092	2.68	1.97	1.588	-4.6E-04	6.2
8	25115	65.1	6.18	1.23	5397	0.0089	3.36	2.24	1.588	-6.0E-04	7.2
9	25108	65.1	6.18	1.37	6050	0.0086	4.11	2.52	1.587	-7.5E-04	8.2
10	25100	65.1	6.18	1.52	6702	0.0084	4.92	2.79	1.587	-9.3E-04	9.3
11	25090	65.1	6.18	1.67	7355	0.0082	5.79	3.06	1.586	-1.1E-03	10.5
12	25080	65.1	6.19	1.82	8008	0.0080	6.72	3.34	1.586	-1.3E-03	11.7
13	25068	65.0	6.19	1.97	8661	0.0079	7.71	3.61	1.585	-1.5E-03	12.9
14	25055	65.0	6.19	2.11	9314	0.0077	8.76	3.88	1.584	-1.8E-03	14.3
	25041			2.26							
	ΔPtotal	103	Pa	m_{evap}	1775	$kg\ h^{-1}$					

Effect 3

L	P	T	V-v	G	Re	f	Terms				ΔP
	Pa	°C	$m^3\ kg^{-1}$	[-]	[-]	[-]	1	2	3	4	Pa
0	17252	56.9	8.79	0.41	1870	0.0086	0.53	0.97	1.116	-6.9E-05	2.6
1	17249	56.9	8.79	0.55	2467	0.0065	0.70	1.27	1.116	-1.2E-04	3.1
2	17246	56.9	8.79	0.68	3065	0.0102	1.70	1.58	1.116	-1.8E-04	4.4
3	17242	56.9	8.79	0.81	3663	0.0098	2.32	1.89	1.116	-2.6E-04	5.3
4	17236	56.9	8.80	0.94	4260	0.0094	3.02	2.20	1.115	-3.6E-04	6.3
5	17230	56.9	8.80	1.08	4858	0.0091	3.80	2.51	1.115	-4.6E-04	7.4
6	17223	56.9	8.80	1.21	5455	0.0088	4.66	2.82	1.114	-5.9E-04	8.6
7	17214	56.9	8.81	1.34	6053	0.0086	5.59	3.13	1.114	-7.2E-04	9.8
8	17204	56.9	8.81	1.47	6651	0.0084	6.59	3.44	1.113	-8.7E-04	11.2
9	17193	56.8	8.82	1.61	7248	0.0082	7.67	3.75	1.113	-1.0E-03	12.5
10	17180	56.8	8.82	1.74	7846	0.0081	8.82	4.07	1.112	-1.2E-03	14.0
11	17166	56.8	8.83	1.87	8443	0.0079	10.03	4.38	1.111	-1.4E-03	15.5
12	17151	56.8	8.84	2.00	9041	0.0078	11.32	4.69	1.110	-1.6E-03	17.1
13	17134	56.8	8.85	2.14	9639	0.0077	12.67	5.01	1.109	-1.8E-03	18.8
14	17115	56.7	8.85	2.27	10236	0.0076	14.09	5.32	1.108	-2.1E-03	20.6
	17094			2.40							
	ΔPtotal	157	Pa	m_{evap}	1299	$kg\ h^{-1}$					

Effect 4 (96 tubes)

L	P	T	V-v	G	Re	f	Terms				ΔP
	Pa	°C	$m^3\ kg^{-1}$	[-]	[-]	[-]	1	2	3	4	Pa
0	12530	50.3	11.87	0.26	1181	0.0135	0.43	0.81	0.827	-2.6E-05	2.1
1	12528	50.3	11.87	0.39	1793	0.0089	0.66	1.23	0.826	-6.1E-05	2.7
2	12525	50.3	11.87	0.52	2405	0.0067	0.88	1.65	0.826	-1.1E-04	3.4
3	12522	50.3	11.88	0.66	3017	0.0103	2.14	2.07	0.826	-1.7E-04	5.0
4	12517	50.3	11.88	0.79	3629	0.0098	2.96	2.49	0.826	-2.5E-04	6.3
5	12510	50.3	11.89	0.92	4241	0.0094	3.89	2.92	0.825	-3.4E-04	7.6
6	12503	50.3	11.89	1.06	4853	0.0091	4.93	3.34	0.825	-4.5E-04	9.1
7	12494	50.2	11.90	1.19	5465	0.0088	6.07	3.76	0.824	-5.6E-04	10.7
8	12483	50.2	11.91	1.32	6077	0.0086	7.32	4.19	0.824	-7.0E-04	12.3
9	12471	50.2	11.92	1.45	6689	0.0084	8.67	4.61	0.823	-8.5E-04	14.1
10	12457	50.2	11.93	1.59	7301	0.0082	10.11	5.04	0.822	-1.0E-03	16.0
11	12441	50.2	11.95	1.72	7913	0.0081	11.65	5.47	0.821	-1.2E-03	18.0
12	12423	50.1	11.97	1.85	8525	0.0079	13.29	5.90	0.820	-1.4E-03	20.0
13	12403	50.1	11.98	1.99	9137	0.0078	15.03	6.33	0.819	-1.6E-03	22.2
14	12380	50.1	12.00	2.12	9749	0.0076	16.87	6.77	0.817	-1.8E-03	24.5
	12356			2.25							
	ΔPtotal	174	Pa	m_{evap}	1462	$kg\ h^{-1}$					

Effect 4 (80 tubes)

L	P	T	V-v	G	Re	f	Terms				ΔP
	Pa	°C	$m^3\ kg^{-1}$	[-]	[-]	[-]	1	2	3	4	Pa
0	12593	50.4	11.81	0.31	1418	0.0113	0.52	1.16	0.830	-3.8E-05	2.5
1	12591	50.4	11.81	0.47	2152	0.0074	0.79	1.76	0.830	-8.8E-05	3.4
2	12588	50.4	11.82	0.63	2886	0.0055	1.05	2.37	0.830	-1.6E-04	4.3
3	12583	50.4	11.82	0.79	3621	0.0098	2.94	2.97	0.830	-2.5E-04	6.7
4	12577	50.4	11.83	0.95	4355	0.0094	4.06	3.58	0.829	-3.6E-04	8.5
5	12568	50.4	11.84	1.11	5089	0.0090	5.33	4.18	0.829	-4.9E-04	10.3
6	12558	50.3	11.84	1.27	5824	0.0087	6.76	4.79	0.828	-6.4E-04	12.4
7	12545	50.3	11.86	1.43	6558	0.0084	8.32	5.40	0.827	-8.1E-04	14.6
8	12531	50.3	11.87	1.59	7292	0.0082	10.03	6.01	0.827	-1.0E-03	16.9
9	12514	50.3	11.88	1.75	8027	0.0080	11.88	6.62	0.826	-1.2E-03	19.4
10	12495	50.2	11.90	1.90	8761	0.0079	13.87	7.24	0.824	-1.5E-03	22.0
11	12473	50.2	11.92	2.06	9495	0.0077	16.00	7.86	0.823	-1.7E-03	24.7
12	12448	50.2	11.94	2.22	10230	0.0076	18.26	8.48	0.821	-2.0E-03	27.6
13	12420	50.1	11.97	2.38	10964	0.0074	20.65	9.11	0.820	-2.3E-03	30.7
14	12390	50.1	12.00	2.54	11698	0.0073	23.19	9.74	0.818	-2.6E-03	33.8
	12356			2.70							
	ΔPtotal	238	Pa	m_{evap}	1462	$kg\ h^{-1}$					

A-13 Additional photographs of fouling

A-13.1 Whole Milk on 26 May 2004 after 22 hours before cleaning

The fouling in these photos was caused by the lack of a DSI filter and poor design of the distribution and spray plates. Corrections by Fonterra have minimised this fouling.

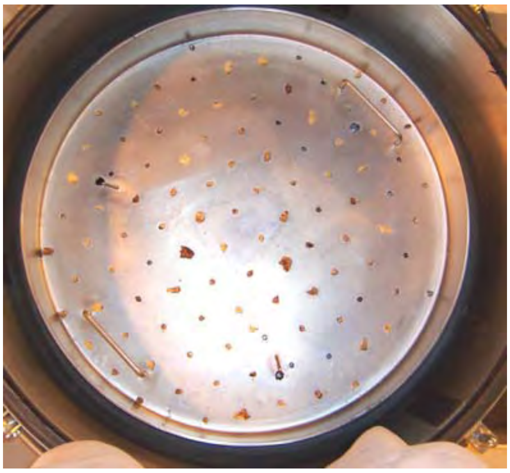
Evaporator 1 effect 4

Evaporator 2 effect 4

Evaporator 2 effect 4

Evaporator 2 effect 3 spray plate

A-13.2 MPC on 29 September 2004 before manual and chemical cleaning

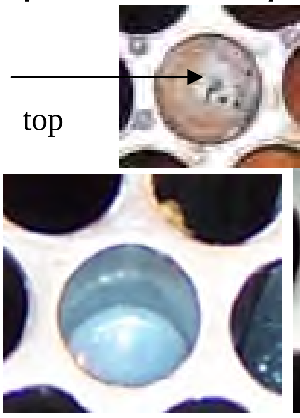


Evaporator 4 effect 3

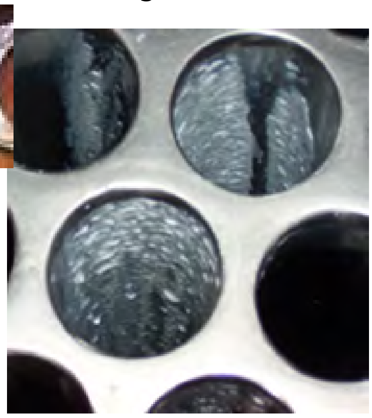
Evaporator 4 effect 4

A-13.3 MPC-85 on 5 April 2005 after 5 hours but before cleaning

Evaporator 4 effect 4

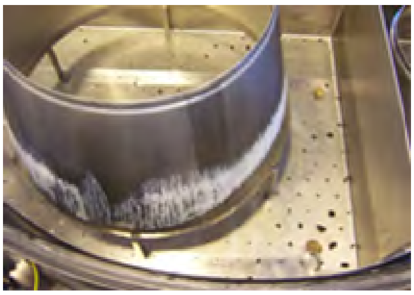


Evaporator 4 effect 2 pass 5 blocked tube



Fouling on the top of tubes

Evaporator 4 effect 2 before cleaning



Evaporator 4 effect 2 pass 1 before cleaning

Evaporator 4 effect 4 sprayer before cleaning

Evaporator 3 effect 2 pass 4 before cleaning

A-14. Boiling Regimes

Source: Incropera and DeWitt (1990).